OCT 1948

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AXIAL-FLOW TURBOJET ENGINE

IV - PERFORMANCE AND WINDMILLING DRAG CHARACTERISTICS

By Carl L. Meyer and Harry E. Bloomer

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
August 23, 1948

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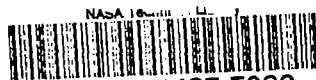
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SUMMARY

An investigation has been conducted in the NACA Cleveland alti-
tude wind tunnel to evaluate the performance and windmilling drag
characteristics of an original and a modified turbojet engine of the
same type. Data have been obtained at simulated altitudes from 5000
to 45,000 feet, simulated flight Mach numbers from 0.09 to 1.08, and
engine speeds from 4000 to 12,500 rpm. Engine performance data are
presented for both engines to show the effects of altitude at a
flight Mach number of 0.25 and of flight Mach number at an altitude
of 25,000 feet. Performance of the original and modified engines is
compared for a range of simulated flight conditions. The performance
data are generalized to show the applicability of methods used to
estimate performance at any altitude from data obtained at a given
altitude. Engine-windmilling-speed and windmilling-drag data are
presented for a range of simulated flight conditions.

Performance variables depending upon fuel consumption that are
obtained from data at one altitude cannot be used to predict these
variables at other altitudes; however, thrust and air-flow values
can be predicted for a limited range of altitudes from data taken at
one altitude. The exhaust-nozzle-outlet total temperature increased
at high engine speeds as the altitude was raised, and decreased at
all engine speeds as the flight Mach number was increased for a
limited range of flight Mach numbers. At engine speeds greater than
10,000 rpm, the specific fuel consumption based on net thrust was
not appreciably affected by changes in altitude from 5000 to
35,000 feet, but was markedly increased by a further increase in
altitude to 45,000 feet. In general, the specific fuel consumption
based on net thrust increased as the flight Mach number was increased.
The net thrust at maximum engine speed for the modified engine was
3 to 20 percent greater than that of the original engine; the spe-
cific fuel consumption based on net thrust at maximum engine speed

was comparable for the two engines. For an airspeed of 500 miles
per hour at an altitude of 25,000 feet, the windmilling drag was
approximately equal to 11 percent of the maximum net thrust at that
flight condition.

INTRODUCTION

An investigation has been conducted in the NACA Cleveland alti-
tude wind tunnel to evaluate the performance characteristics of an
original and a modified turbojet engine of the same type. The main
components of the engines were similar except that the modified
engine included changes made by the manufacturer to improve velocity
and temperature distributions within the engine. Data have been
obtained for a range of simulated altitudes and flight Mach numbers
throughout the operable range of engine speeds. Extensive instru-
mentation was installed in the engines to obtain detailed information
on the individual components of the engines, as well as over-all
engine performance. Analyses of turbine performance, compressor per-
formance, combustion-chamber performance, and operational character-
istics are presented in references 1, 2, 3, and 4, respectively.

Engine performance data are presented herein to show the effects
of altitude at a flight Mach number of 0.25 and of flight Mach number
at an altitude of 25,000 feet. Performance of the original and
modified engines is compared for a range of simulated flight condi-
tions. The applicability of methods used to generalize the data in
order to estimate the performance at various altitudes from perform-
ance data obtained at a given altitude is discussed. Data are also
presented to show the effects of altitude and airspeed on engine
windmilling speed and windmilling drag.

DESCRIPTION OF ENGINE

The X24C-4B turbojet engine used in the altitude-wind-tunnel
investigation has a sea-level static thrust rating of 3000 pounds at
an engine speed of 12,500 rpm. At this rating, the air flow is
approximately 58.5 pounds per second and the fuel consumption is
3200 pounds per hour. The engine has an 11-stage axial-flow com-
pressor with a pressure ratio of approximately 3.8 at rated engine
speed, a double-annulus combustion chamber, a two-stage turbine, and
a fixed-area exhaust nozzle. The over-all length of the engine is
$119\frac{1}{2}$ inches, the maximum diameter is $28\frac{1}{4}$ inches, and the total weight
is 1150 pounds. The modified engine was similar to the original
engine except for minor changes made by the manufacturer in the com-
pressor and the combustion chamber.

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Air enters the engine through an annular inlet and passes into the compressor through a single row of inlet guide vanes. The compressors of the original and modified engines were similar with the exception of the eleventh-stage rotor blading. For the modified engine, the loading on the eleventh-stage rotor blades was reduced in order to obtain a more nearly uniform velocity distribution at the compressor outlet. This reduced loading was accomplished by twisting the blades, in the direction of reduced angle of attack, 3° at the midspan and 6° at the tip. A more complete description of the compressors is given in reference 2.

After being compressed, the air is discharged from the compressor through two rows of straightening vanes and an annular diffuser into the double-annulus combustion chamber. Fuel is injected into the two annuli of the combustion chamber from two concentric fuel manifolds. There are 36 fuel nozzles in the outer manifold ring and 24 in the inner manifold ring. The fuel nozzles for the original engine had a rated capacity of $7\frac{1}{2}$ gallons per hour at a differential pressure of 100 pounds per square inch, as compared with 7 gallons per hour for the modified engine. The fuel used throughout the investigation conformed to specification AN-F-28, Amendment 3. Air entering the combustion chamber is divided into three annular streams by the two concentric fuel manifolds. For the original engine, a screen having 60-percent blocking area was installed in the outer annular air stream and one of 40-percent blocking area was installed in the intermediate annular air stream. For the modified engine, these screens were replaced by two screens of 30-percent blocking area.

The double-annulus combustion chamber (reference 3) is of the step type. Steps 1 and 2 admit primary air through small circular wall perforations. For the original engine, secondary air entered the combustion chamber through rows of circular holes in steps 3 and 4. For the modified engine, secondary air entered the combustion chamber through a single row of large rectangular holes in step 3. The total area of the combustion-chamber-wall perforations was the same for the original and modified engines.

Gases from the combustion chamber flow through the two-stage turbine into the tail pipe and exhaust through a fixed-area exhaust nozzle. Each turbine stage consists of a stator and a rotor. The turbine rotor assembly includes the shaft and the first- and second-stage disks. A more complete description of the turbine, which was similar for the original and modified engines, is given in reference 1.

As a result of the various changes included in the modified
engine, the manufacturer raised the allowable operating temperature
limit for this engine. The maximum temperature, as indicated by
any thermocouple at the turbine outlet, was limited to 1250° F for
the original engine as compared with 1400° F for the modified engine.
The engine modifications and the revised temperature limit permitted
a reduction in exhaust-nozzle-outlet area from 183 square inches
for the original engine to 171 square inches for the modified engine.

INSTALLATION AND PROCEDURE

The engines were installed in a wing nacelle in the test sec-
tion of the altitude wind tunnel (fig. 1). For this installation,
an extended inlet duct 5 feet long and an extended tail pipe 3 feet
long were used. Cowling was eliminated from around the engine.
Instrumentation was installed at several stations in the engine
(fig. 2). The instrumentation installed in the original and modi-
fied engines was the same except at the turbine outlet, where addi-
tional thermocouples were installed for the modified engine to give
a more complete temperature survey.

Inlet pressures corresponding to the desired flight Mach num-
bers were obtained by introducing dry refrigerated air from the
tunnel make-up air system through a duct to the engine inlet. This
air was throttled from approximately sea-level pressure to the
desired total pressure at the compressor inlet; the static pressure
in the wind-tunnel test section was maintained at the pressure
corresponding to the desired altitude. The duct from the tunnel
make-up air system was attached to the engine inlet duct by means
of a slip joint with a labyrinth seal in order that drag and thrust
values could be determined by use of the tunnel balance scales.

Engine performance data were obtained at simulated altitudes
from 5000 to 45,000 feet, simulated flight Mach numbers from 0.09
to 1.08, and engine speeds from idling speed (4000 rpm) to rated
speed (12,500 rpm). The compressor-inlet air temperatures were
held at approximately NACA standard values corresponding to the
simulated flight conditions, except at high altitudes and low
flight Mach numbers; no inlet-air temperatures below 440° R were
obtained. At the high altitudes, the maximum engine speed was
limited by the turbine-outlet temperature and minimum engine speed
was limited by combustion blow-out.

Thrust was determined by calculation from tunnel balance-scale
measurements and also by calculation from pressure and temperature

measurements obtained at the exhaust-nozzle outlet (station 8).
Power-off drag runs were made in order to correct the balance-scale
measurements for external-drag forces. The values of thrust pre-
sented herein were obtained from measurements made with the tunnel
balance scales. Air flow was calculated from pressure and tempera-
ture measurements obtained at the engine inlet (station 1). Com-
plete ram-pressure recovery was assumed at the compressor inlet in
the calculation of equivalent airspeed and flight Mach number. The
symbols and the methods of calculation used in this report are pre-
sented in the appendix.

RESULTS AND DISCUSSION

Because no inlet-air temperatures below 440° R were obtained,
the equivalent ambient static temperatures were considerably above
the standard values at high altitudes and low flight Mach numbers.
The various altitude performance data presented in this report have
been corrected to the standard altitude temperatures by use of the
factor θ_a, the ratio of absolute ambient static temperature to
absolute ambient static temperature of NACA standard atmosphere at
the respective altitude. Performance data corrected by this method
may be somewhat different from data obtained under actual conditions
because of the effect of Reynolds number on compressor performance.

An examination of the data has shown that the average ratio of
the jet thrust calculated from tunnel balance-scale measurements to
the jet thrust calculated from temperature and pressure measurements
obtained at the exhaust-nozzle outlet was 0.987 for the original
engine and 0.976 for the modified engine. The values of thrust pre-
sented in this report were calculated from balance-scale measure-
ments except for those instances where the aforementioned jet-thrust
ratio deviated considerably from the respective average ratio.
Where this deviation was encountered, the specific fuel consumption
based on balance-scale measurements of net thrust was inconsistent
and, therefore, the jet thrust was taken as the product of the jet-
thrust ratio and the jet thrust calculated from measurements at the
exhaust-nozzle outlet. Net thrust, presented in the following
discussion, was determined by subtracting the initial free-stream
momentum of the inlet air from the jet thrust.

Engine Performance

Effect of altitude. - Performance data obtained with both engines
at a constant flight Mach number of 0.25 at altitudes from 5000 to

45,000 feet are presented to show the effect of altitude on the
variation with engine speed of net thrust (fig. 3), air flow
(fig. 4), fuel consumption (fig. 5), specific fuel consumption based
on net thrust (fig. 6), fuel-air ratio (fig. 7), and exhaust-nozzle-
outlet total temperature (fig. 8). The trends of the performance
data for the original and modified engines are similar.

At engine speeds greater than 10,000 rpm, the specific fuel
consumption based on net thrust (fig. 6) was not appreciably
affected by changes in altitude from 5000 to 35,000 feet, but was
markedly increased when the altitude was further raised to
45,000 feet. Fuel-air ratio (fig. 7) increased as the altitude was
raised; the increase in fuel-air ratio became more pronounced at
high altitudes. The minimum fuel-air ratio at each altitude
occurred at an engine speed between 9000 and 10,000 rpm.

The average total temperature measured at the exhaust-nozzle
outlet increased at high engine speeds as the altitude was raised
(fig. 8). For engine speeds below approximately 10,500 rpm,
increasing the altitude to 25,000 feet decreased the exhaust-
nozzle-outlet total temperature. Increasing the altitude from
25,000 to 35,000 feet decreased the temperature at engine speeds
below 10,000 rpm for the original engine and at engine speeds
between 8000 and 9500 rpm for the modified engine. A further
increase in altitude to 45,000 feet increased the temperature at
all engine speeds.

Effect of flight Mach number. - Performance data obtained with
both engines at an altitude of 25,000 feet and flight Mach numbers
from 0.25 to 1.08 are presented to show the effect of flight Mach
number on the variation with engine speed of net thrust (fig. 9), air
flow (fig. 10), fuel consumption (fig. 11), specific fuel consumption
based on net thrust (fig. 12), fuel-air ratio (fig. 13), and exhaust-
nozzle-outlet total temperature (fig. 14). In general, the perform-
ance trends of the original and modified engines are similar.

Raising the flight Mach number from 0.25 to 0.53 decreased
the net thrust (fig. 9) throughout the entire range of engine speeds.
As the flight Mach number was increased beyond 0.53, the net thrust
decreased at low engine speeds and increased at high engine speeds.

As the flight Mach number was raised, the fuel consumption
(fig. 11) decreased at low engine speeds and increased at high engine
speeds. For the original engine, the specific fuel consumption based
on net thrust (fig. 12(a)) increased at all engine speeds as the
flight Mach number was raised to 0.98, but was unaffected by a

further increase in flight Mach number to 1.08. For the modified engine, the specific fuel consumption based on net thrust (fig. 12(b)) increased at all engine speeds as the flight Mach number was increased to 1.08. For the original engine, raising the flight Mach number reduced the fuel-air ratio (fig. 13(a)) throughout the range of engine speeds. For the modified engine, raising the flight Mach number to 0.87 reduced the fuel-air ratio throughout the range of engine speeds; however, a further increase in flight Mach number to 1.08 resulted in increased fuel-air ratios at high engine speeds.

At all engine speeds, for the original engine, the exhaust-nozzle-outlet total temperature (fig. 14(a)) was reduced as the flight Mach number was increased to 0.98, but was not appreciably affected by further increasing the flight Mach number to 1.08. For the modified engine, the exhaust-nozzle-outlet total temperature (fig. 14(b)) was reduced at all engine speeds as the flight Mach number was raised to 0.73; at high engine speeds, however, the temperature was not appreciably affected as the flight Mach number was increased from 0.73 to 0.87, but was increased by a further increase in flight Mach number to 1.08.

Comparison of engines. - Maximum engine speed was either the rated engine speed of 12,500 rpm or a temperature-limited engine speed that was less than 12,500 rpm. The instrumentation installed at the turbine outlet was different for the two engines; 25 thermocouples were used in determining the average turbine-outlet temperature for the original engine as compared with 49 thermocouples for the modified engine. The measured turbine-outlet temperatures of the original engine are considered to be lower than the actual temperatures. For the purposes of this report, however, the temperature-limited engine speed of the original engine is defined as that engine speed at which the average turbine-outlet indicated temperature was 1520° R. For the modified engine, the temperature-limited engine speed is defined as that engine speed at which the average turbine-inlet total temperature (calculated from turbine-outlet total temperature by the method given in reference 1) is 1885° R. These average-temperature limits correspond approximately to the maximum turbine-outlet temperature limits used when the engines were in operation.

The performance of the original engine is compared with that of the modified engine on the basis of the variation of net thrust (fig. 15) and of specific fuel consumption based on net thrust (fig. 16) with airspeed at maximum engine speed. The data of these figures were obtained from figures 3, 6, 9, and 12, and from similar additional figures. The maximum engine speed was 12,500 rpm at

altitudes of 5000 and 15,000 feet for the range of airspeeds inves-
tigated and at an altitude of 25,000 feet for airspeeds greater than
approximately 365 miles per hour for the original engine and
420 miles per hour for the modified engine. At the lower airspeeds
at an altitude of 25,000 feet and for the range of airspeeds inves-
tigated at altitudes of 35,000 and 45,000 feet, however, the maximum
engine speed was a temperature-limited engine speed less than
12,500 rpm.

For the range of airspeeds investigated, the net thrust at max-
imum engine speed of the modified engine (fig. 15) was greater than
that of the original engine by 7 to 20 percent at an altitude of
15,000 feet, 5 to 14 percent at an altitude of 25,000 feet, approx-
imately 6 percent at an altitude of 35,000 feet, and 3 to 19 percent
at an altitude of 45,000 feet. As the airspeed was increased
within the range investigated, the difference between the net thrust
at maximum engine speed of the modified engine and that of the
original engine increased at altitudes of 15,000 and 25,000 feet,
was essentially unaffected at an altitude of 35,000 feet, and
decreased at an altitude of 45,000 feet.

For the range of airspeeds investigated, the specific fuel
consumption based on net thrust for the modified engine at maximum
engine speed (fig. 16) was equal to or less than that for the
original engine except at equivalent airspeeds greater than
600 miles per hour at an altitude of 25,000 feet and 275 miles per
hour at an altitude of 35,000 feet. In most cases, however, the
specific fuel consumption based on net thrust for the modified
engine at maximum engine speed was within 2 percent of that for
the original engine.

Generalized Performance

The altitude performance data presented in figures 3 to 8 have
been generalized to standard sea-level conditions by use of the
factors δ and θ . The generalized performance data are presented
in figures 17 through 22. The concept of flow similarity and the
application of dimensional analysis has led to the development of
these factors with which data obtained at several altitudes may be
generalized. In the development of this method of generalization,
the efficiencies of the engine components were considered to be
unaffected by changes in altitude. Any changes in component effi-
ciencies therefore lessen the possibility of generalizing data
obtained at different altitudes to a single curve.

Data obtained with both engines at a constant flight Mach number of 0.25 at altitudes from 5000 to 45,000 feet are compared to show the effect of altitude on the corrected values of net thrust (fig. 17), air flow (fig. 18), fuel consumption (fig. 19), specific fuel consumption based on net thrust (fig. 20), fuel-air ratio (fig. 21), and exhaust-nozzle-outlet total temperature (fig. 22).

Net-thrust data (fig. 17) generalized to a single curve at altitudes up to 25,000 feet for the range of corrected engine speeds and at all altitudes at low corrected engine speeds. At high corrected engine speeds, however, the corrected net thrust increased as the altitude was raised above 25,000 feet. The air-flow data (fig. 18) generalized to a single curve for all engine speeds at altitudes up to 15,000 feet for the original engine and at altitudes up to 25,000 feet for the modified engine; further increases in altitude reduced the corrected air flow at all corrected engine speeds.

Corrected fuel consumption (fig. 19), corrected specific fuel consumption based on net thrust (fig. 20), corrected fuel-air ratio (fig. 21), and corrected exhaust-nozzle-outlet total temperature (fig. 22) increased markedly as the altitude was raised.

Turbine, compressor, and combustion efficiencies decreased over most of the operating range of engine speeds as the altitude was raised (references 1, 2, and 3, respectively). Because of the effect of altitude on compressor and turbine efficiencies, higher corrected temperatures within the engine were required as the altitude was raised; the increase in corrected temperature as the altitude was raised is shown in figure 22. Increased corrected temperatures and corrected pressures within the engine caused the corrected net thrust to increase at high corrected engine speeds as the altitude was raised above 25,000 feet. The decreased component and combustion efficiencies, as the altitude was raised, resulted in increased corrected fuel consumption and, consequently, increased corrected fuel-air ratios and corrected specific fuel consumption based on net thrust.

Performance variables depending upon fuel consumption that are obtained from data at one altitude cannot be used to predict these variables at other altitudes. Thrust and air-flow values, however, can be predicted for a limited range of altitudes from data obtained at one altitude.

Windmilling Drag

The variation of engine windmilling speed and windmilling drag with airspeed at altitudes from 5000 to 45,000 feet is shown in figure 23. The windmilling engine speed is essentially unaffected by changes in altitude and varied almost linearly with airspeed. Windmilling drag, in general, increased as the airspeed was increased and decreased as the altitude was raised. The windmilling engine speed and drag of the two engines are comparable.

The variation of the ratio of windmilling drag to net thrust at maximum engine speed with airspeed at an altitude of 25,000 feet is shown in figure 24. The data of this figure were obtained from figures 15 and 23. An examination of the data from other altitudes has shown that the ratio of windmilling drag to net thrust at maximum engine speed is not appreciably affected by changes in altitude within the range of airspeeds investigated. The windmilling drag is approximately equal to 1 percent of the net thrust at maximum engine speed for an airspeed of 200 miles per hour and increases to 11 percent at an airspeed of 500 miles per hour.

SUMMARY OF RESULTS

An investigation of the performance of two turbojet engines of the same type in the Cleveland altitude wind tunnel at altitudes from 5000 to 45,000 feet and flight Mach numbers from 0.09 to 1.08 gave the following results:

1. Performance variables depending upon fuel consumption that are obtained from data at one altitude cannot be used to predict these variables at other altitudes; however, thrust and air-flow values can be predicted for a limited range of altitudes from data taken at one altitude.

2. Increasing the altitude raised the exhaust-nozzle-outlet total temperature at high engine speeds for both engines. For the original engine, the exhaust-nozzle-outlet total temperature was lowered at all engine speeds by increases in flight Mach number to 0.98 and was unaffected by a further increase in flight Mach number to 1.08. For the modified engine, the exhaust-nozzle-outlet total temperature was lowered at all engine speeds by increases in flight Mach number to 0.73; however, at high engine speeds the temperature was not appreciably affected as the flight Mach number was increased from 0.73 to 0.87 and was raised by a further increase in flight Mach number to 1.08.

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3. At engine speeds greater than 10,000 rpm, specific fuel consumption based on net thrust was not appreciably affected when the altitude was raised from 5000 to 35,000 feet, but was markedly increased when the altitude was further raised to 45,000 feet.

4. In general, the specific fuel consumption based on net thrust increased as the flight Mach number was raised.

5. A comparison of original- and modified-engine performance data showed that the net thrust of the modified engine at maximum engine speed was 3 to 20 percent greater than that of the original engine. In most cases, the specific fuel consumption based on net thrust for the modified engine at maximum engine speed was within 2 percent of that for the original engine.

6. The windmilling engine speed and drag of the two engines are comparable. At an altitude of 25,000 feet, the windmilling drag is approximately equal to 1 percent of the net thrust at maximum engine speed at an airspeed of 200 miles per hour as compared with 11 percent at an airspeed of 500 miles per hour.

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APPENDIX - CALCULATIONS

Symbols

The following symbols are used in this report:

A   cross-sectional area, sq ft

B   thrust-scale reading, lb

c_p specific heat of gas at constant pressure, Btu/(lb)(^oR)

D   external drag of installation, lb

D_w windmilling drag, lb

F_j jet thrust, lb

F_n net thrust, lb

f/a   fuel-air ratio

g   acceleration of gravity, 32.2 ft/sec^2

J   mechanical equivalent of heat, 778 ft-lb/Btu

M_0 flight Mach number

N   engine speed, rpm

P   total pressure, lb/sq ft absolute

p   static pressure, lb/sq ft absolute

R   gas constant, 53.3 ft-lb/(lb)(^oR)

T   total temperature, ^oR

T_i indicated temperature, ^oR

t   static temperature, ^oR

V   velocity, ft/sec

W_a air flow, lb/sec

W_f fuel consumption, lb/hr

W_f/F_n specific fuel consumption based on net thrust,
lb/(hr)(lb thrust)

γ ratio of specific heats

δ ratio of absolute ambient static pressure to absolute
static pressure of NACA standard atmosphere at sea
level

θ ratio of absolute ambient static temperature to absolute
static temperature of NACA standard atmosphere at sea
level

Subscripts:

0   free air stream

x   engine-inlet duct at slip joint

1   engine inlet

2   compressor inlet

8   exhaust-nozzle outlet

The data are generalized to NACA standard sea-level conditions
by the following parameters:

F_n/δ corrected net thrust, lb

$(f/a)/\theta$ corrected fuel-air ratio

$N/\sqrt{\theta}$ corrected engine speed, rpm

T_8/θ corrected exhaust-nozzle-outlet total temperature, $^\circ$R

$(W_a\sqrt{\theta})/\delta$ corrected air flow, lb/sec

$W_f/(\delta\sqrt{\theta})$ corrected fuel consumption, lb/hr

$W_f/(F_n\sqrt{\theta})$ corrected specific fuel consumption based on net thrust,
lb/(hr)(lb thrust)

Methods of Calculation

Thrust. - Thrust was determined by calculation from: (1) tunnel balance-scale measurements, and (2) pressure and temperature measurements obtained at the exhaust-nozzle outlet (station 8). The thrust values presented herein were obtained by use of the first method. Jet thrust was determined from balance-scale measurements by use of the relation

$$F_j = B + D + \frac{W_a}{g} V_x + A_x (p_x - p_0)$$

Jet thrust was determined from pressure and temperature measurements obtained at the exhaust-nozzle outlet by use of the relation

$$F_j = \frac{2\gamma_8}{\gamma_8 - 1} p_8 A_8 \left[\left(\frac{P_8}{p_8} \right)^{\frac{\gamma_8 - 1}{\gamma_8}} - 1 \right] + A_8 (p_8 - p_0)$$

Net thrust was determined from balance-scale measurements by use of the relation

$$F_n = F_j - \frac{W_a}{g} V_0$$

Windmilling drag. - Windmilling drag was determined from balance-scale measurements by use of the relation

$$D_w = \frac{W_a}{g} V_0 - F_j$$

Air flow. - Engine air flow was calculated from pressure and temperature measurements obtained at the engine inlet (station 1) by use of the relation

$$W_a = \frac{p_1 A_1}{R} \sqrt{\frac{2Jgc_p}{t_1} \left[\left(\frac{P_1}{p_1} \right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1 \right]}$$

Temperatures. - Engine-inlet and exhaust-nozzle-outlet temperatures were calculated from the indicated temperature, using a thermocouple recovery factor of 0.85, and respective values of pressure, temperature, and ratio of specific heats:

$$t = \frac{T_1}{1 + 0.85\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

The equivalent ambient static temperature was determined from the relation

$$t_0 = \frac{T_{1,2}}{\left(\frac{P_2}{p_0}\right)^{\frac{\gamma_2-1}{\gamma_2}}}$$

Airspeed. - The airspeed was determined (assuming complete ram-pressure recovery) from the relation

$$V_0 = \sqrt{2Jgc_p t_0 \left[\left(\frac{P_2}{p_0}\right)^{\frac{\gamma_2-1}{\gamma_2}} - 1\right]}$$

Flight Mach number. - The flight Mach number was determined (assuming complete ram-pressure recovery) from the equation

$$M_0 = \sqrt{\frac{2}{\gamma_2 - 1}\left[\left(\frac{P_2}{p_0}\right)^{\frac{\gamma_2-1}{\gamma_2}} - 1\right]}$$

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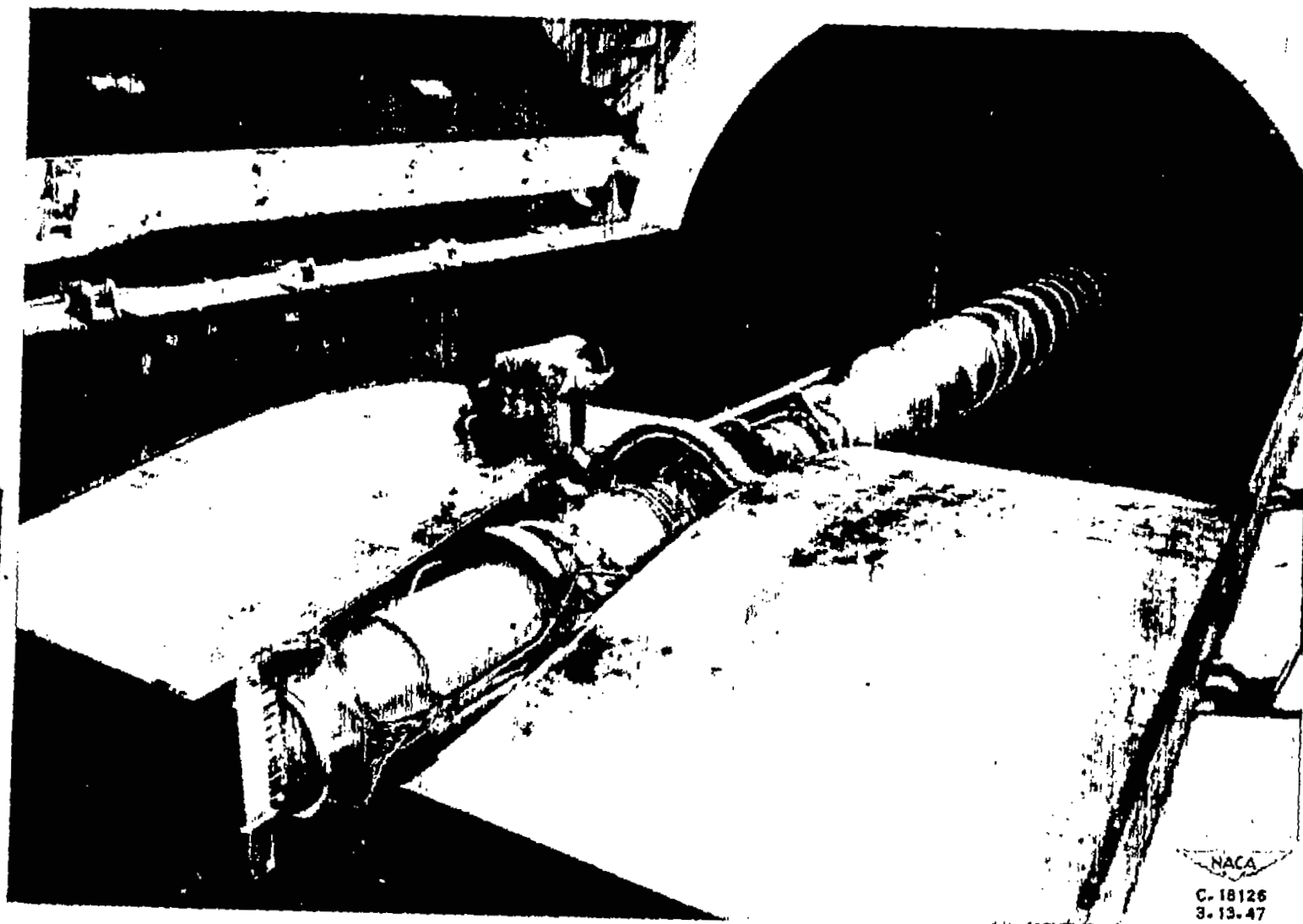
Figure 1. - Installation of turbojet engine in altitude wind tunnel.

Station 7,
turbine
outlet

Station 1,
engine
inlet

Station 2,
compressor
inlet

Station 4,
compressor
outlet

Station 5,
turbine
inlet

Station 8,
exhaust-nozzle
outlet

Air
flow

Engine-
inlet
duct

Compressor

Fuel
manifolds

Combustion
chamber

Turbine

Tail
cone
section

Tail
pipe

Exhaust
nozzle

NACA
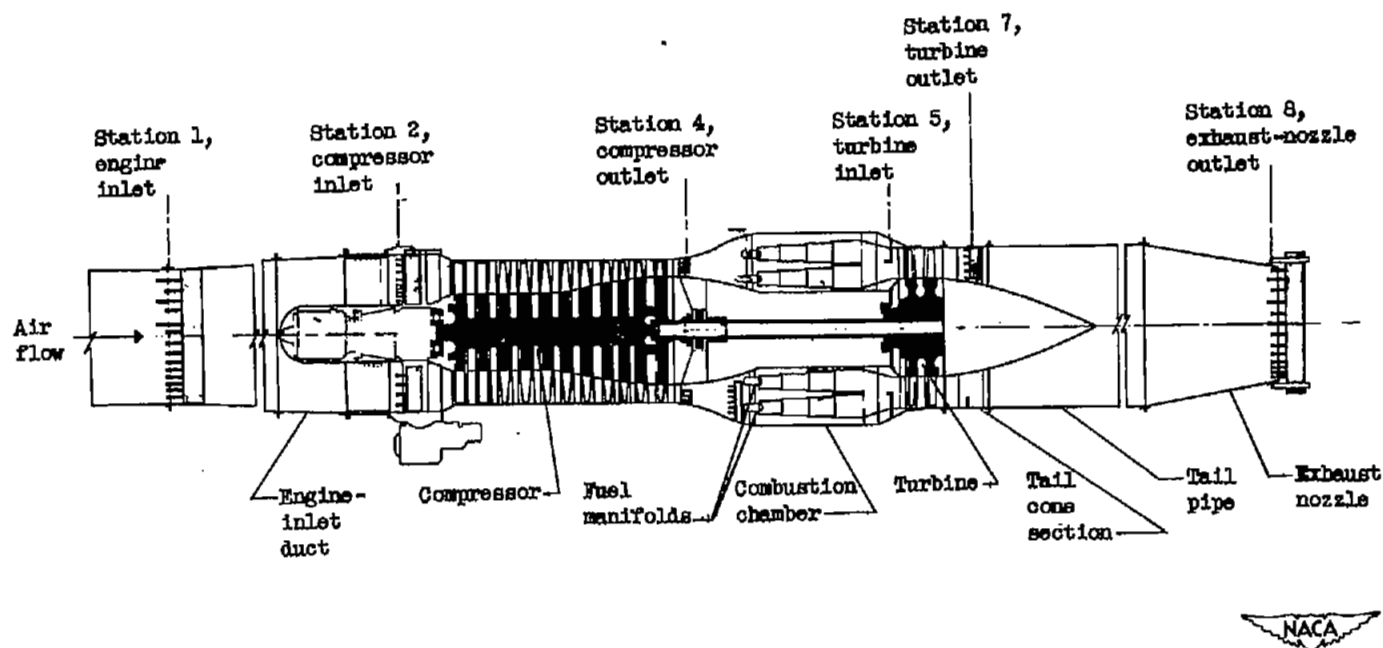
Figure 2. - Location of instrumentation installed in engine.
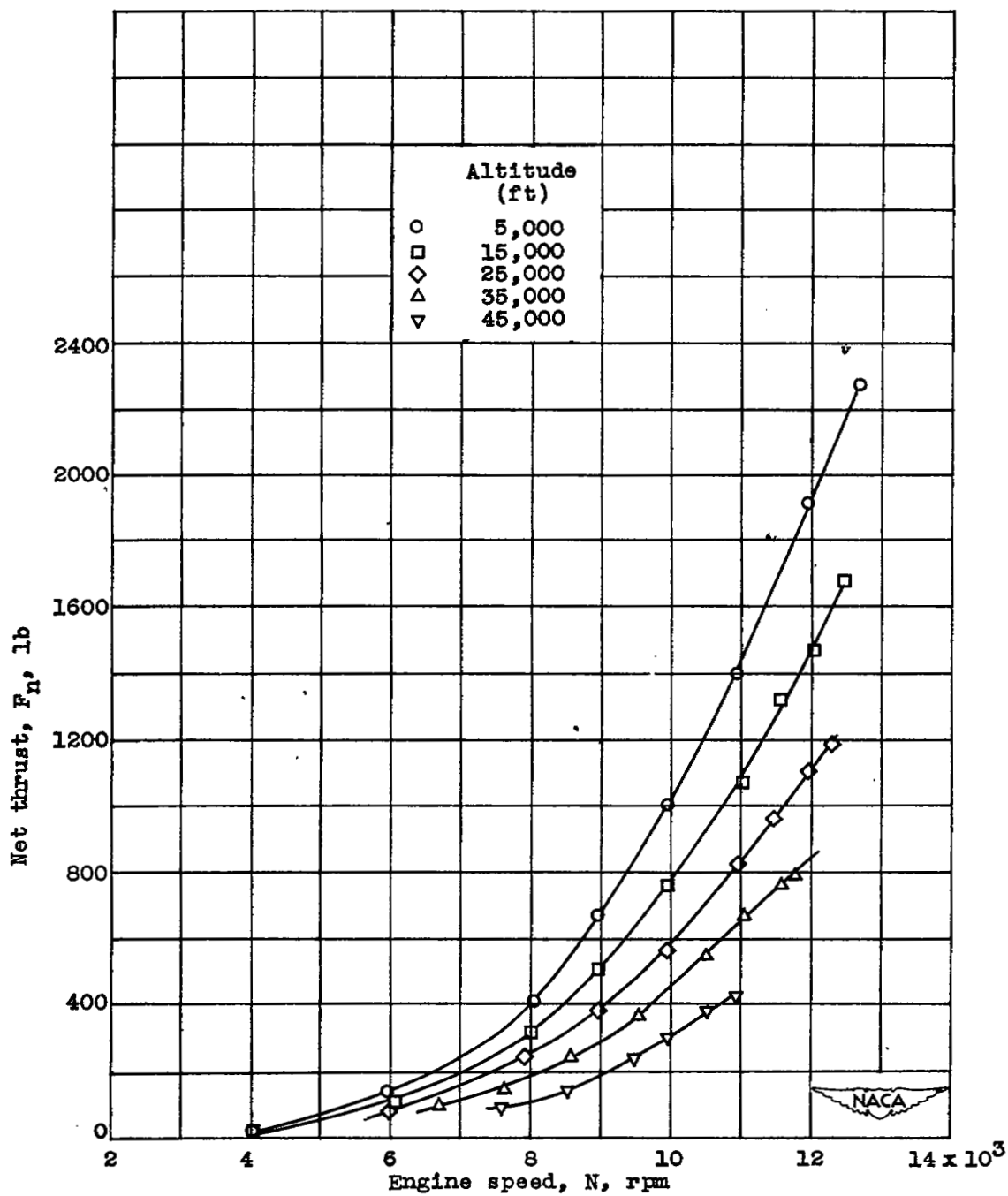
(a) Original engine.

Figure 3. - Effect of altitude on variation of net thrust with
engine speed. Flight Mach number, 0.25.

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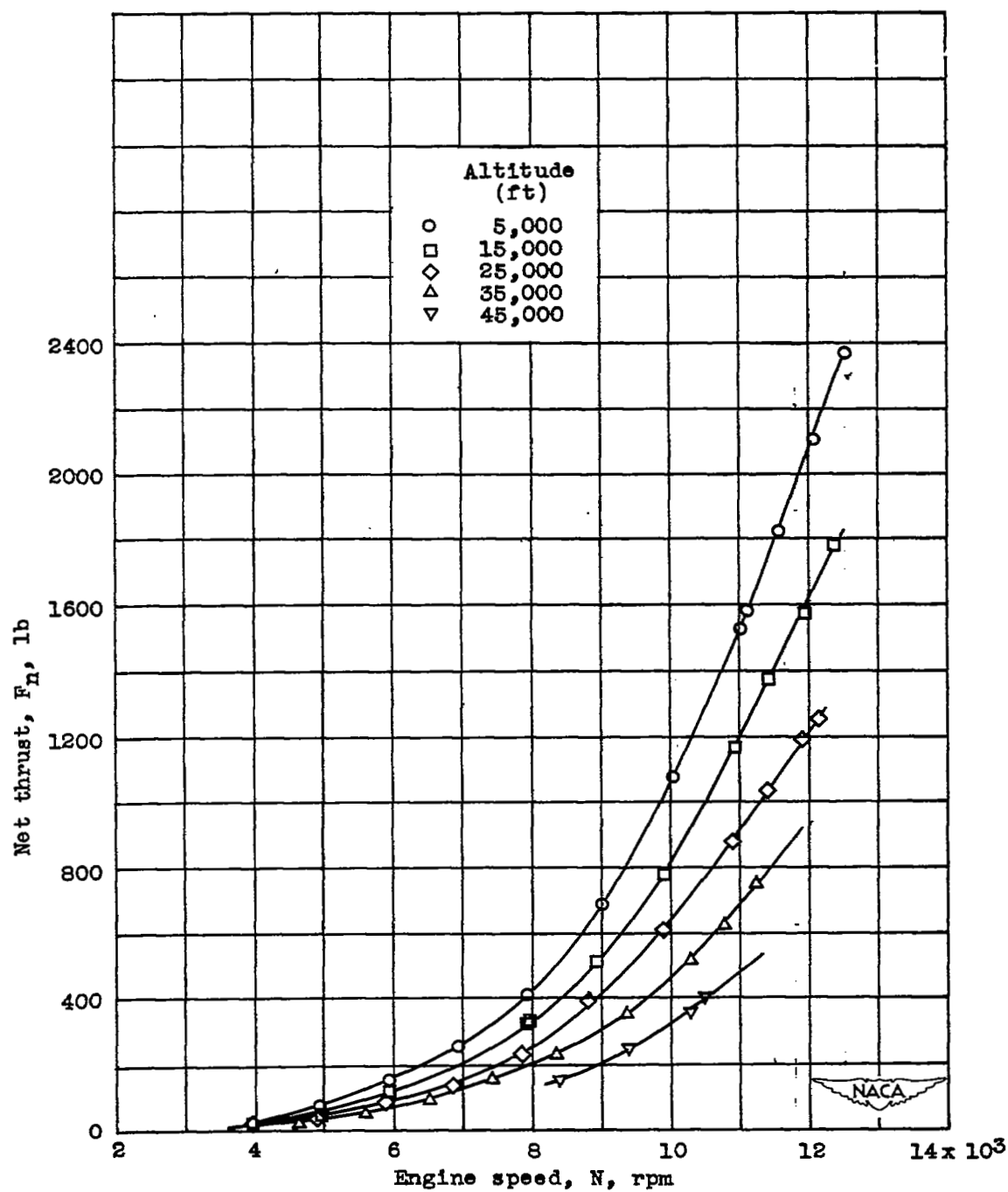
(b) Modified engine.

Figure 3. — Concluded.   Effect of altitude on variation of net thrust with engine speed.   Flight Mach number, 0.25.
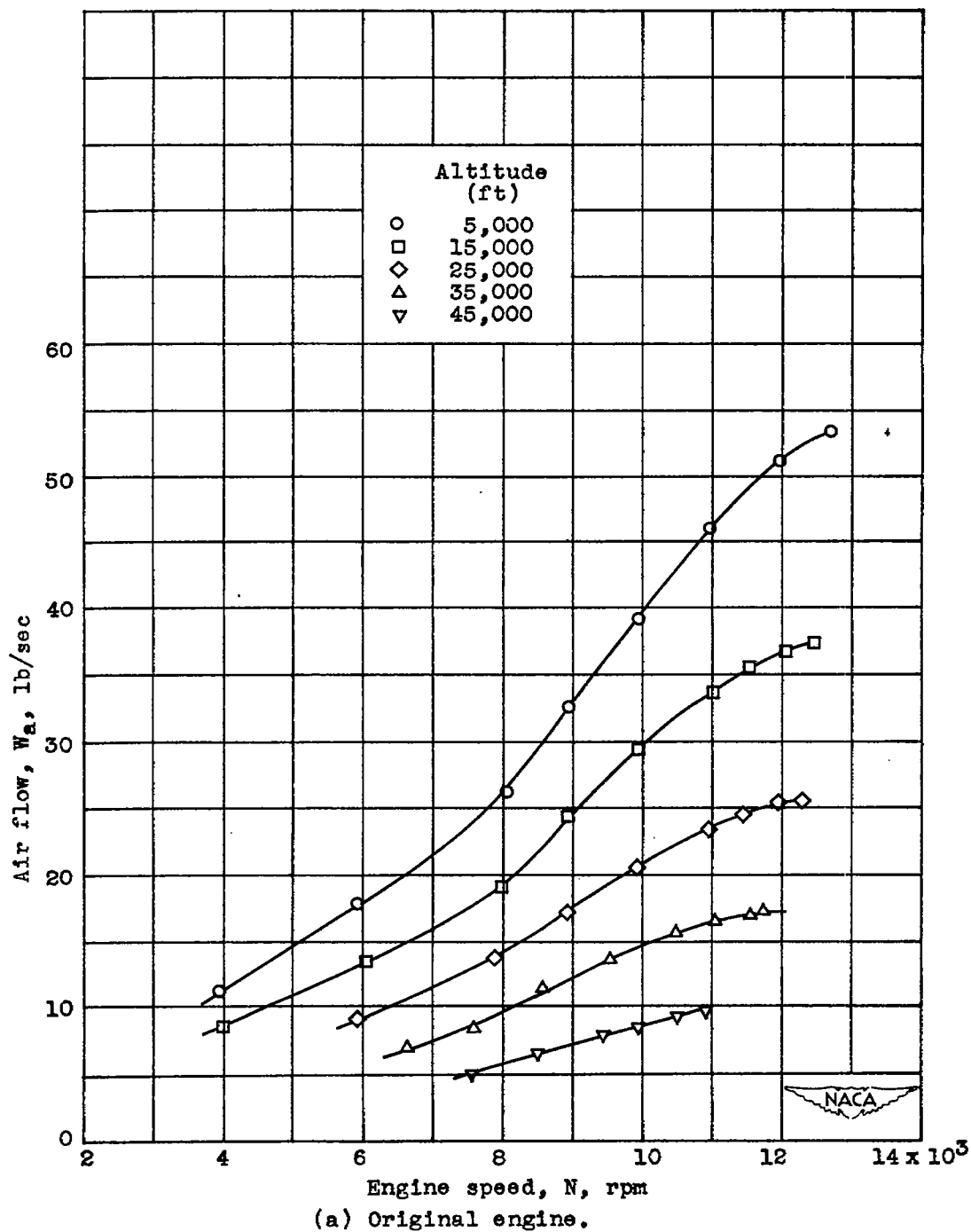
(a) Original engine.

Figure 4. — Effect of altitude on variation of air flow with
engine speed. Flight Mach number, 0.25.

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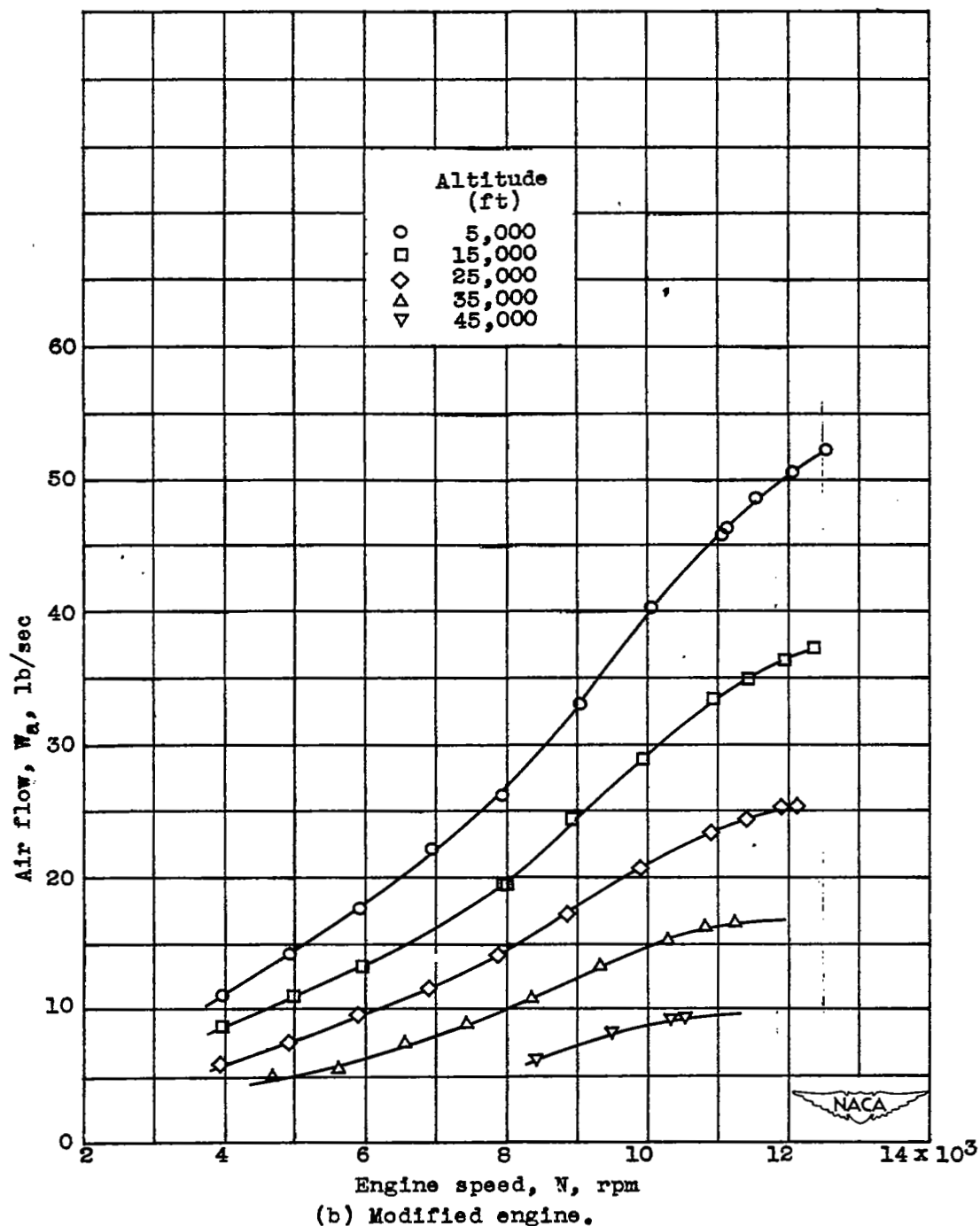
Figure 4. – Concluded. Effect of altitude on variation of air
flow with engine speed. Flight Mach number, 0.25.
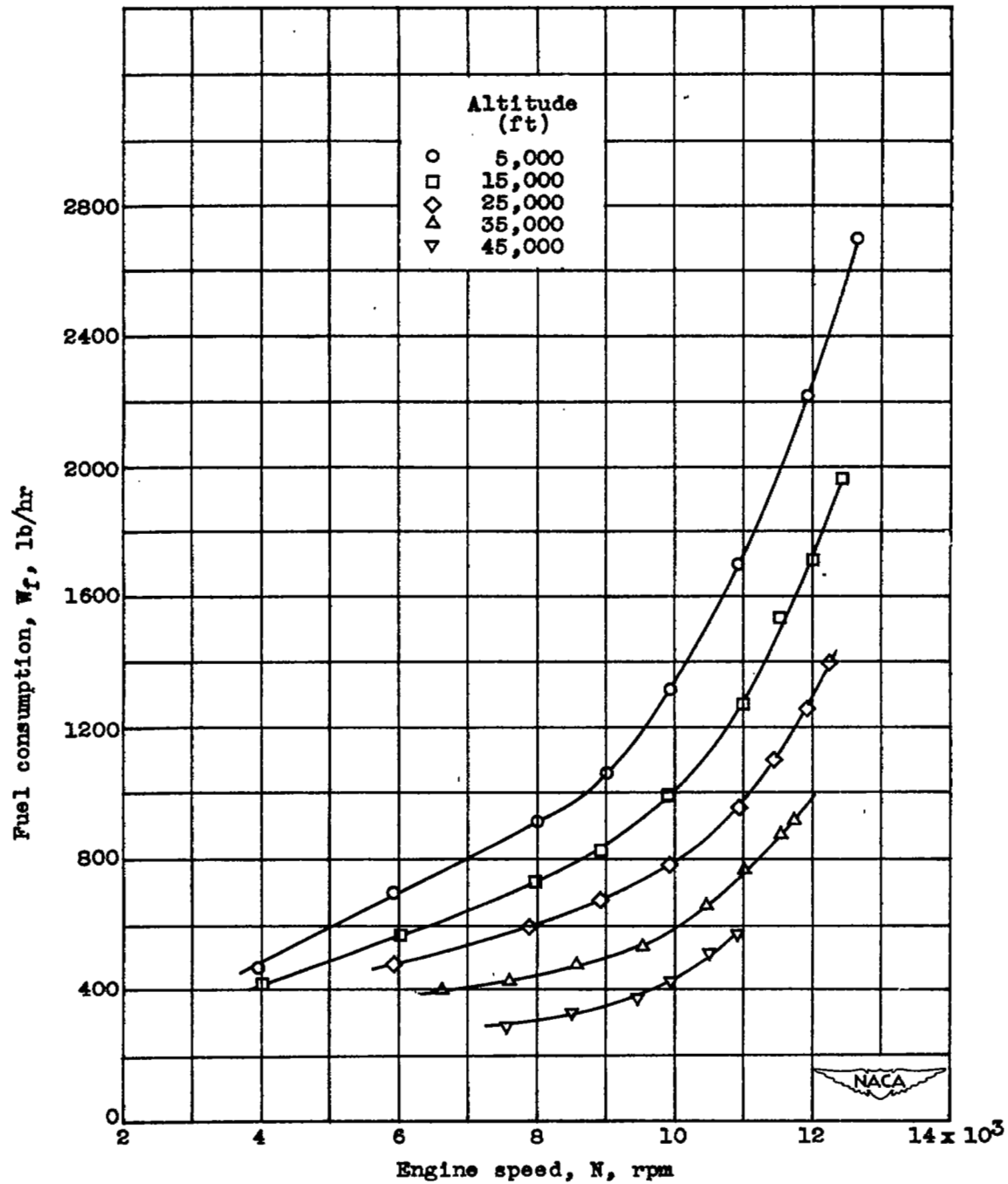
(a) Original engine.

Figure 5. — Effect of altitude on variation of fuel consumption with engine speed. Flight Mach number, 0.25.
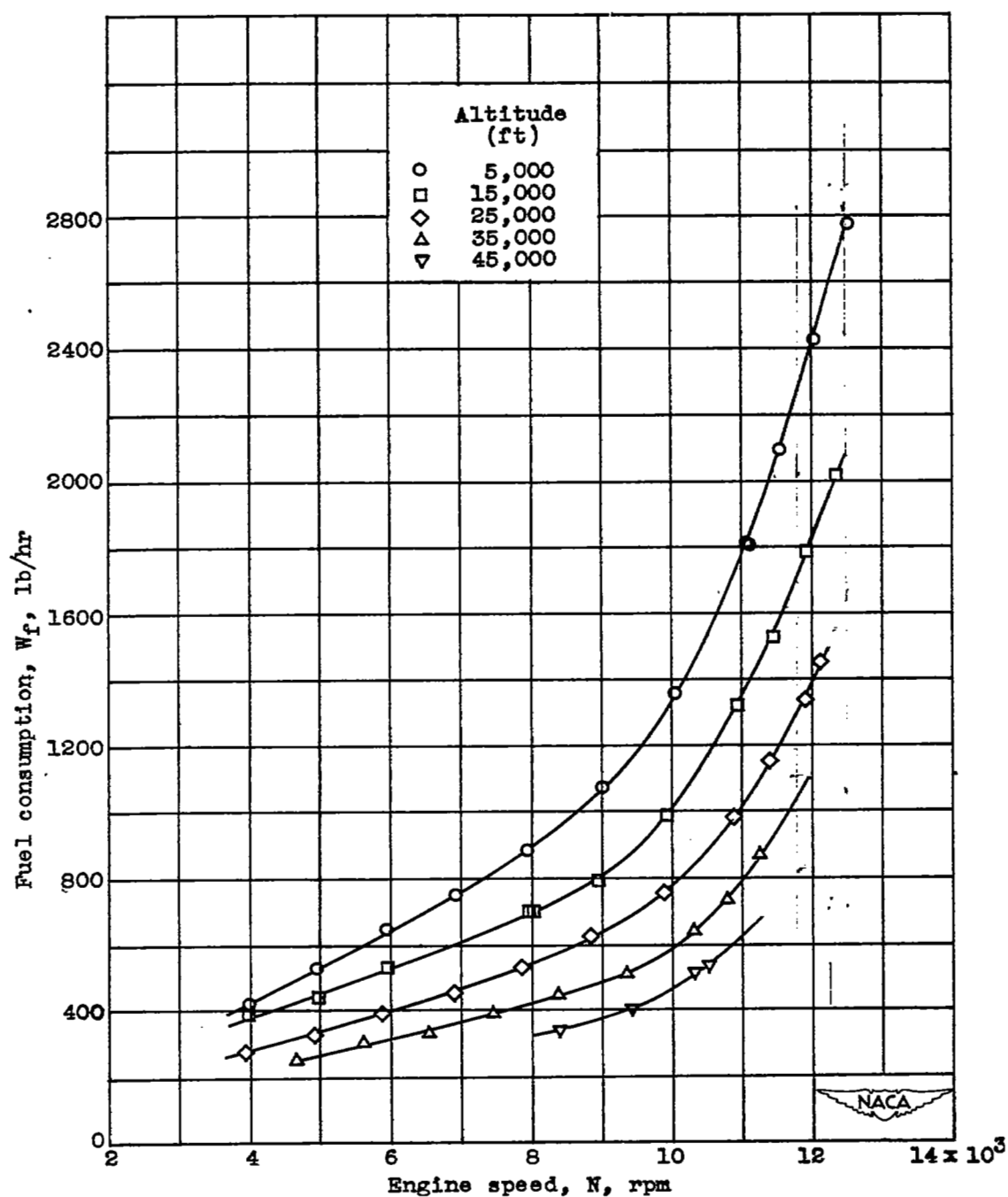
(b) Modified engine.

Figure 5. — Concluded. Effect of altitude on variation of fuel
consumption with engine speed. Flight Mach number, 0.25.
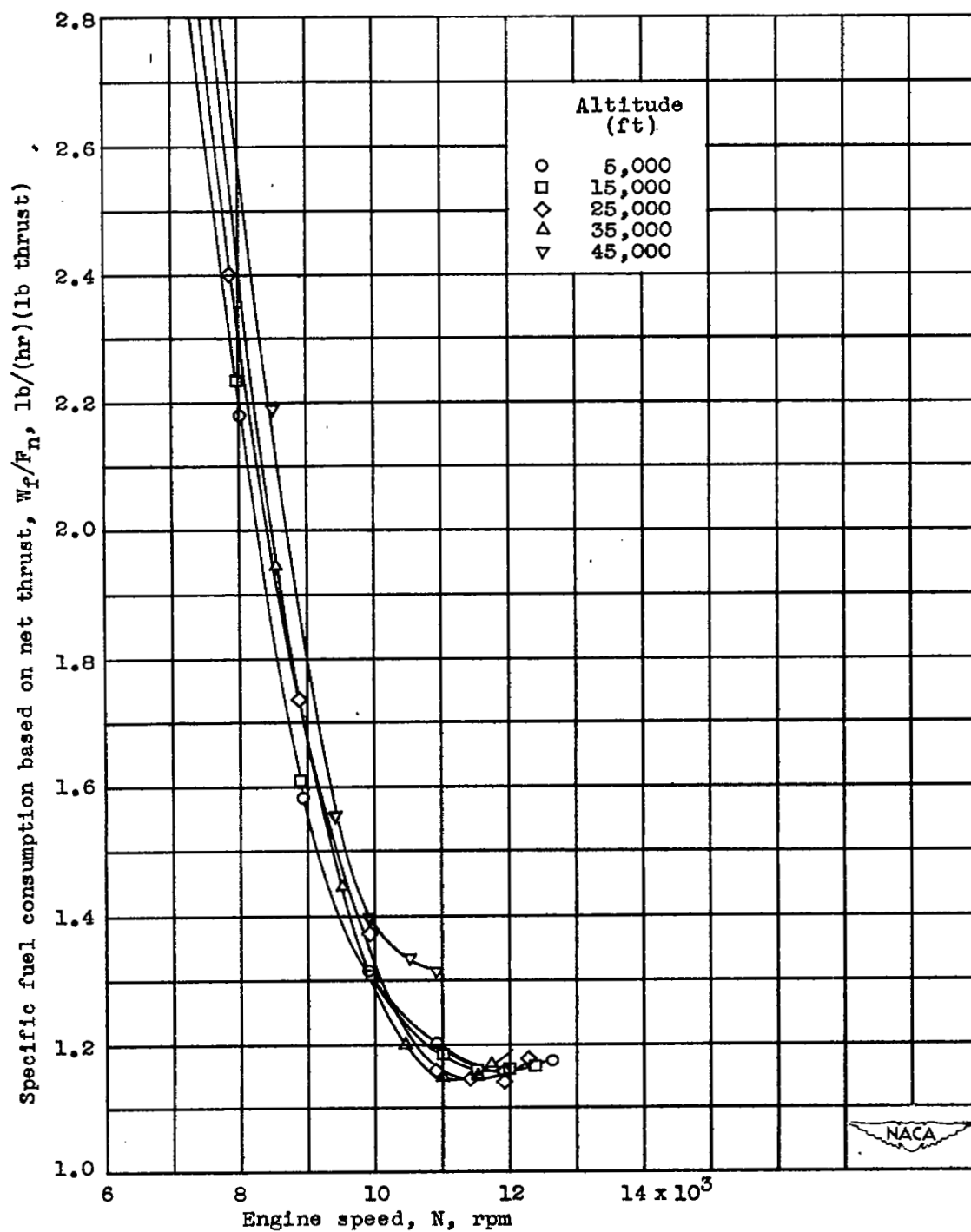
(a) Original engine.

Figure 6. — Effect of altitude on variation of specific fuel con-
sumption based on net thrust with engine speed. Flight Mach
number, 0.25.

(b) Modified engine.
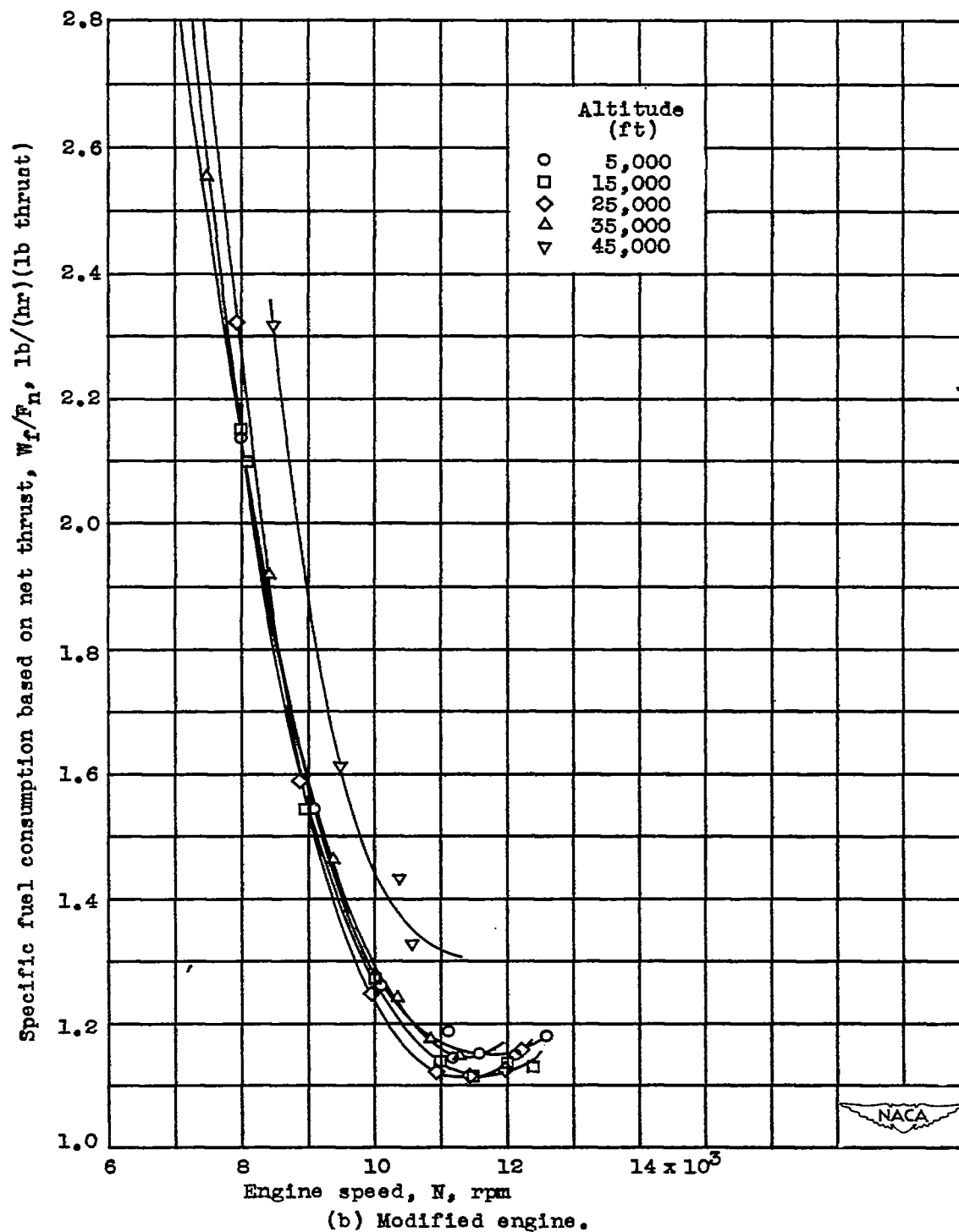
Figure 6. – Concluded. Effect of altitude on variation of specific fuel consumption based on net thrust with engine speed. Flight Mach number, 0.25.

(a) Original engine.
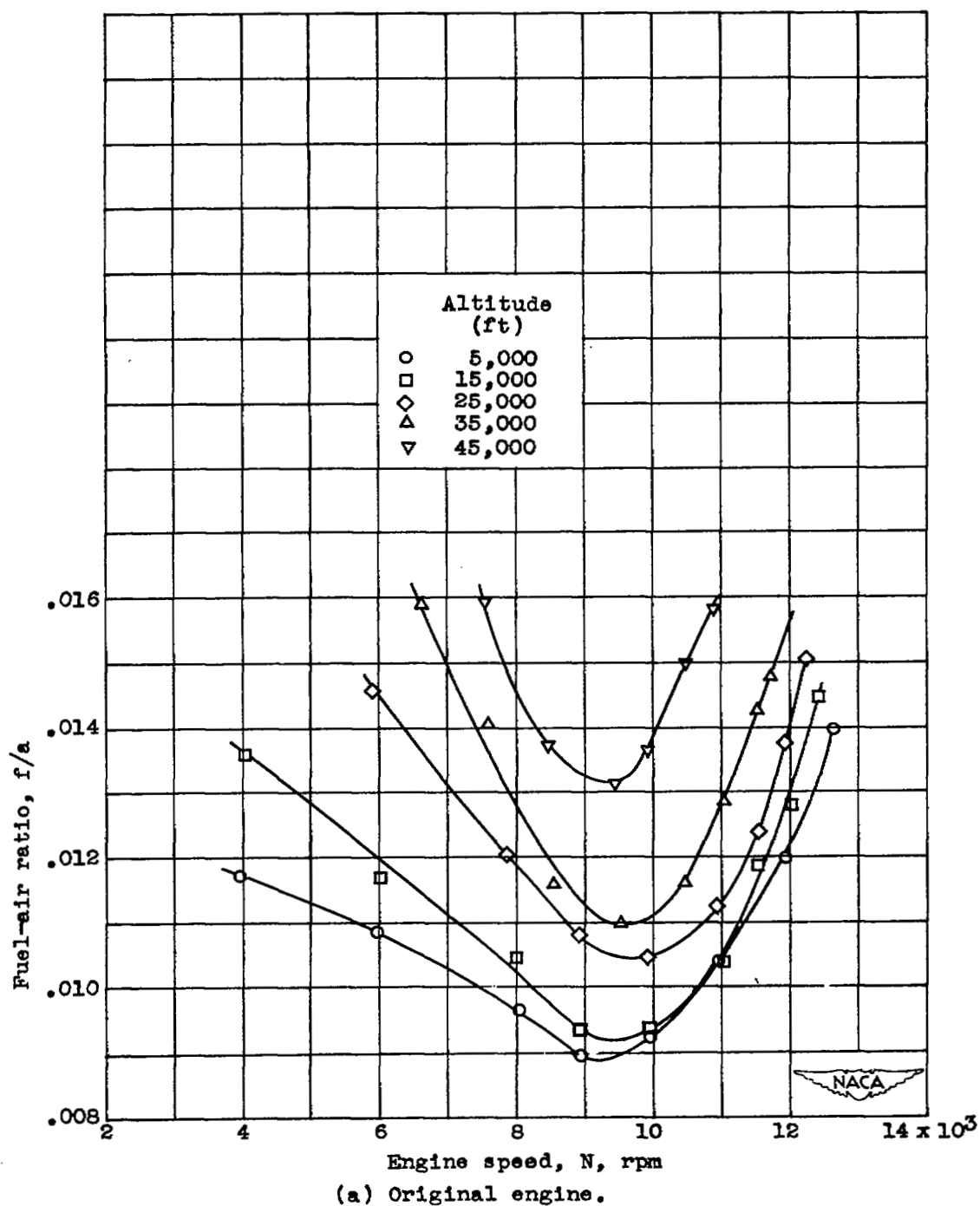
Figure 7. — Effect of altitude on variation of fuel—air ratio
with engine speed. Flight Mach number, 0.25.

(b) Modified engine.
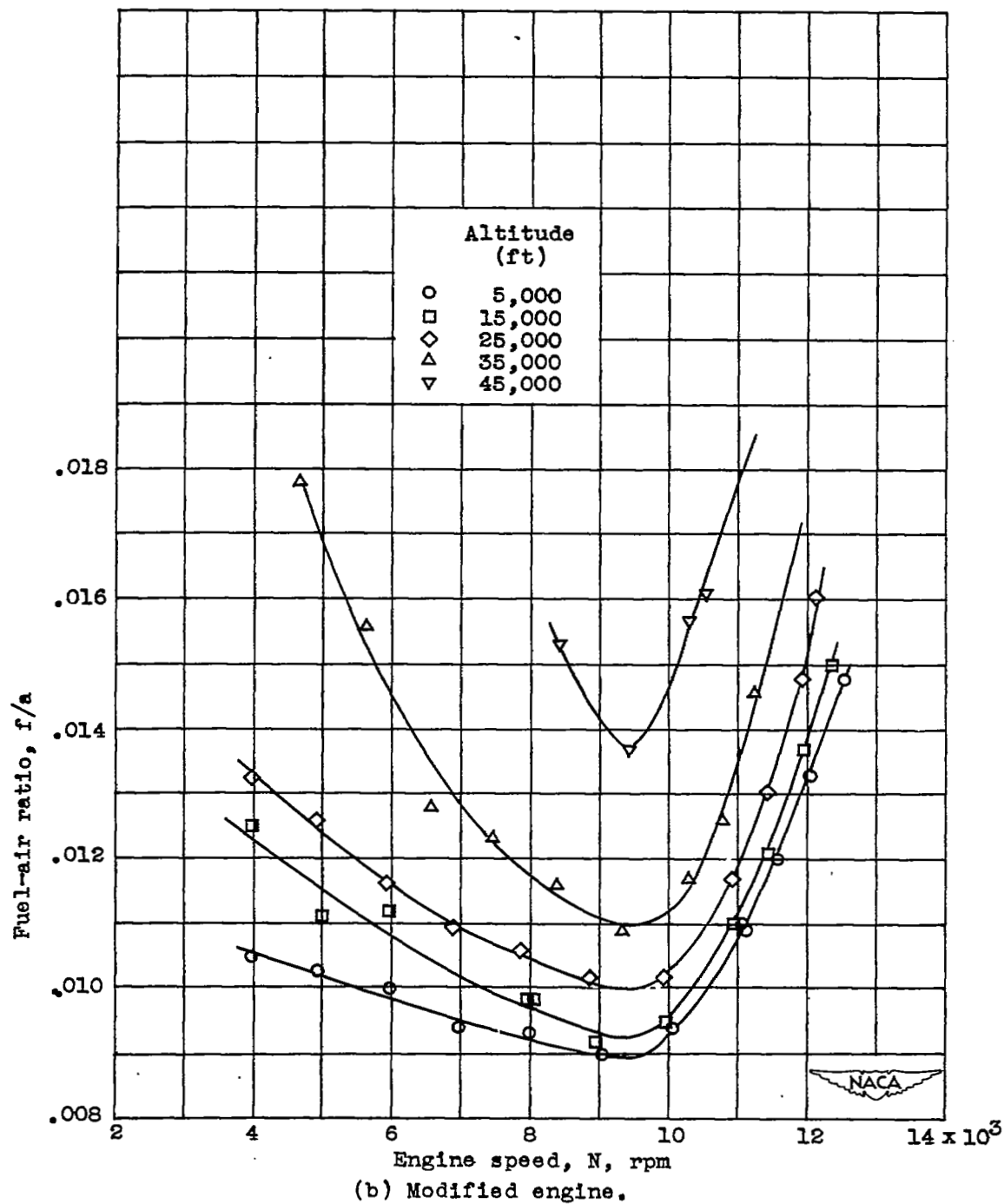
Figure 7. — Concluded. Effect of altitude on variation of fuel-air ratio with engine speed. Flight Mach number, 0.25.

(a) Original engine.
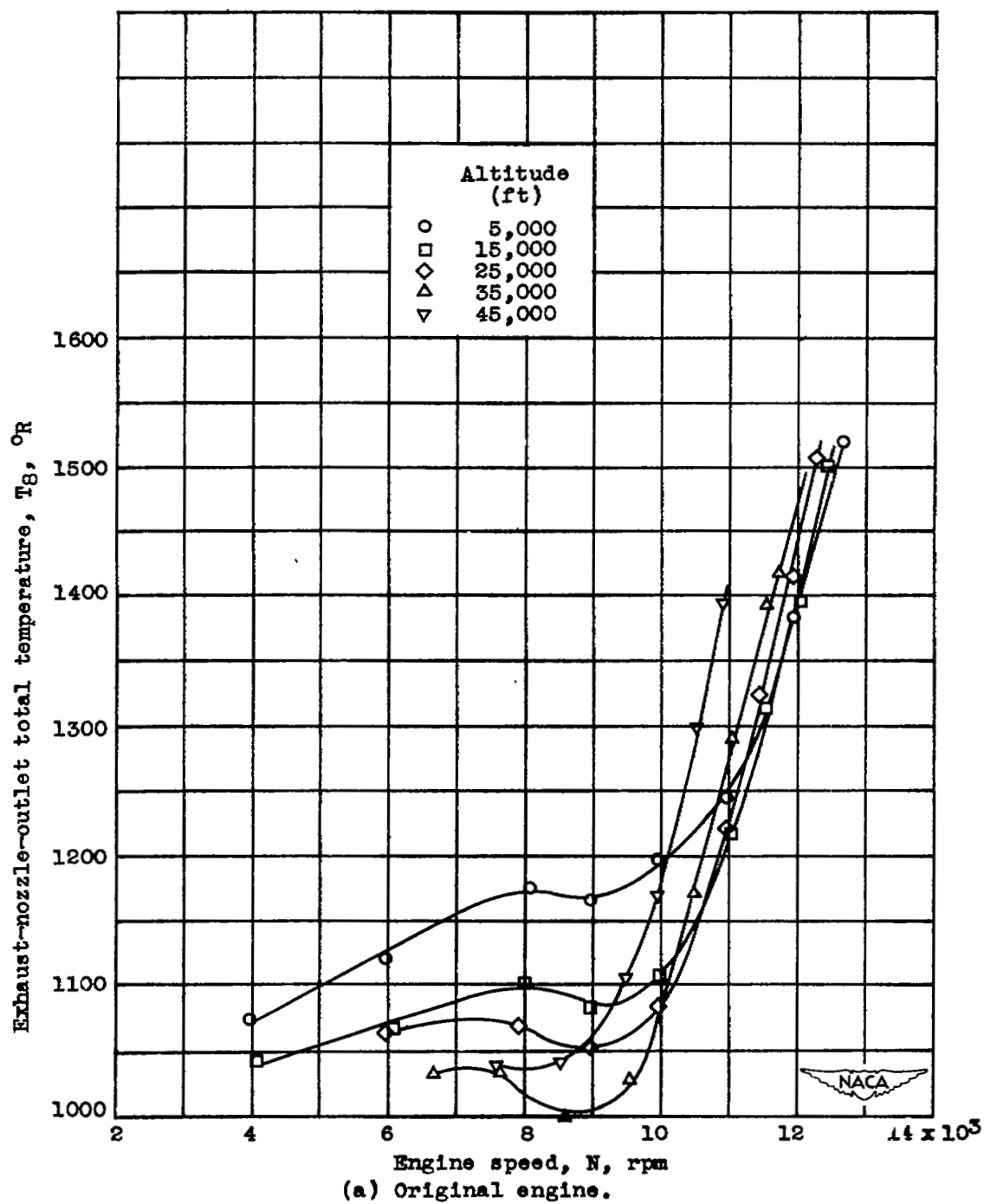
Figure 8. — Effect of altitude on variation of exhaust-nozzle-
outlet total temperature with engine speed. Flight Mach
number, 0.25.

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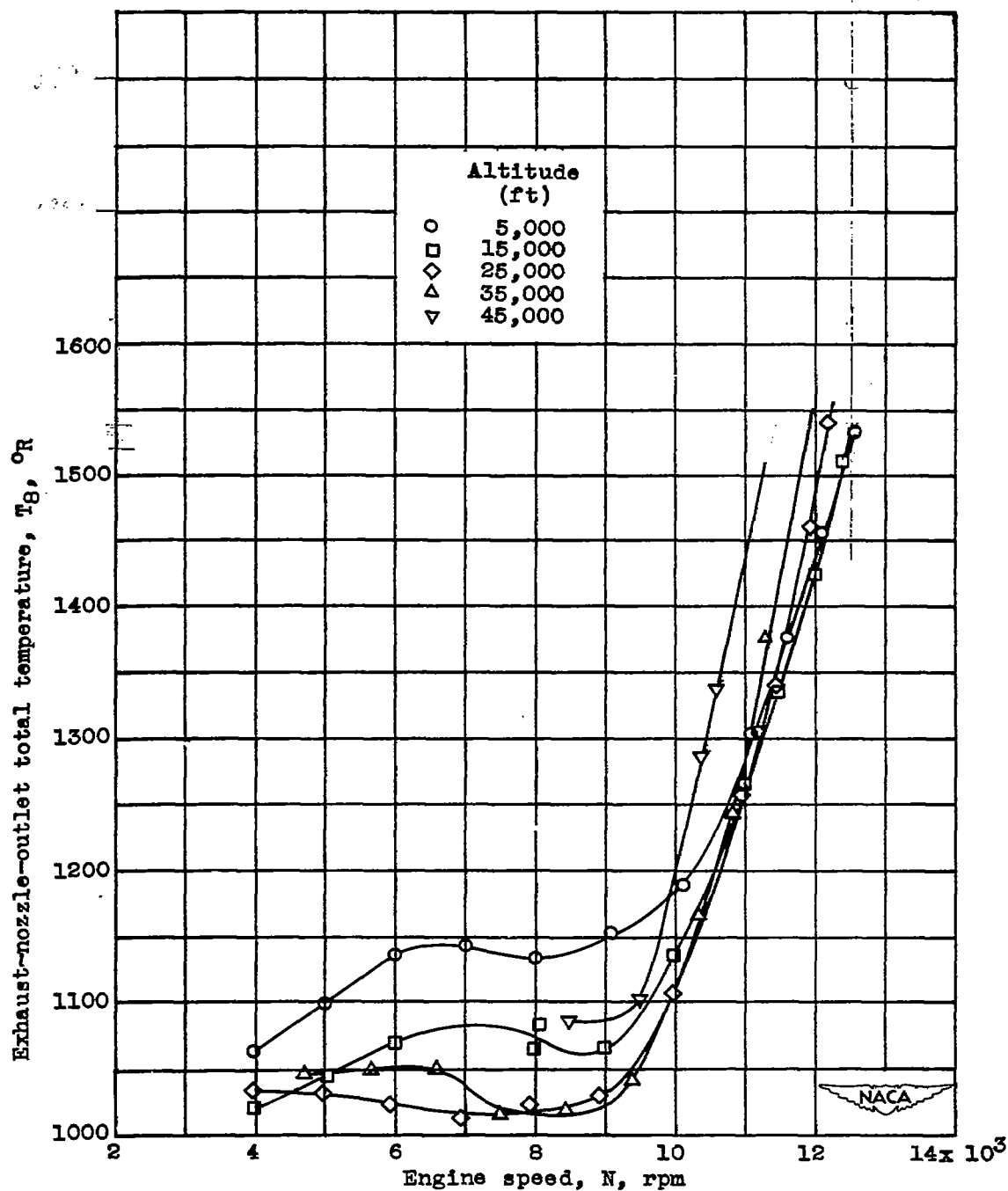
(b) Modified engine.

Figure 8. – Concluded. Effect of altitude on variation of
exhaust–nozzle–outlet total temperature with engine speed.
Flight Mach number, 0.25.

(a) Original engine.
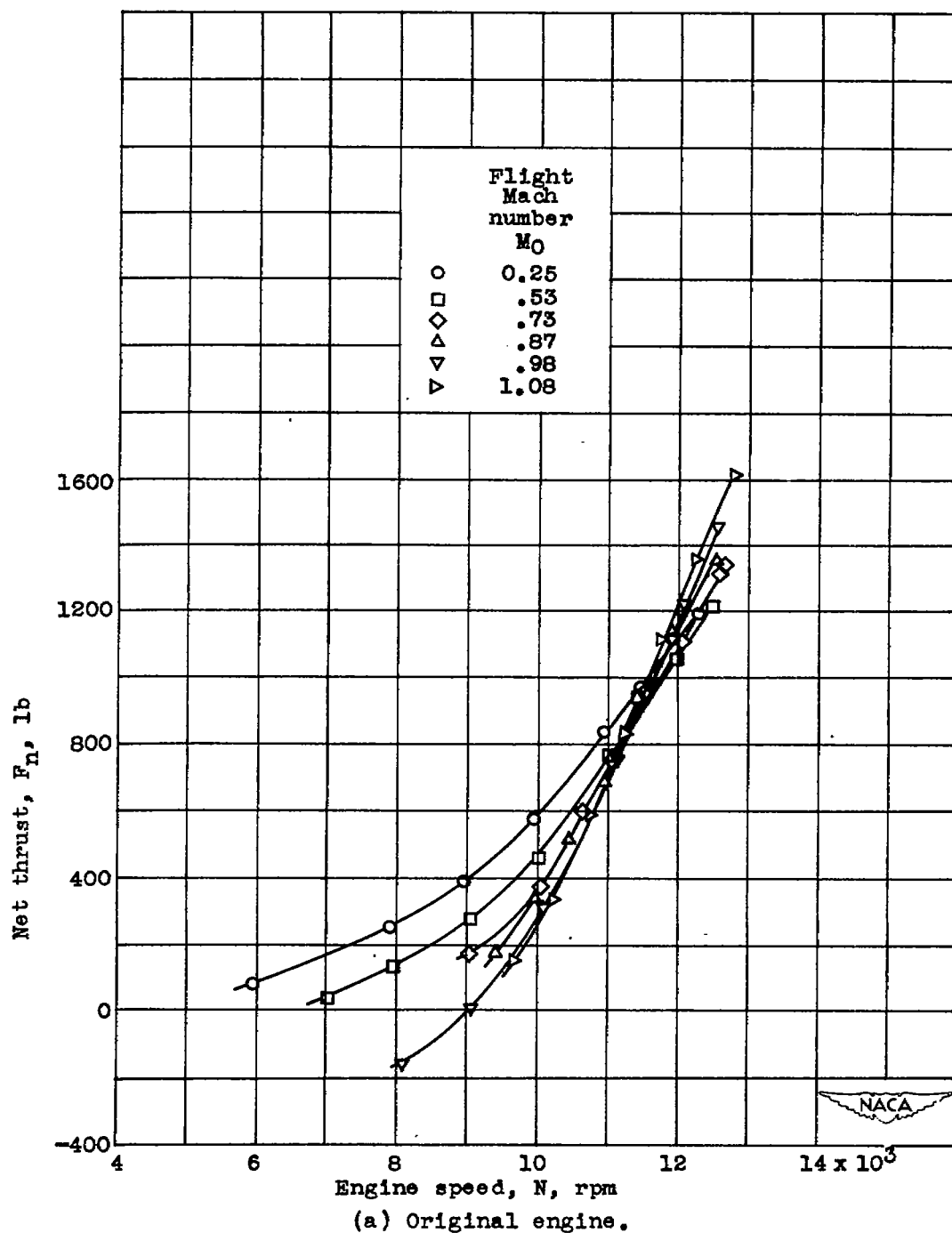
Figure 9. - Effect of flight Mach number on variation of net
thrust with engine speed. Altitude, 25,000 feet.
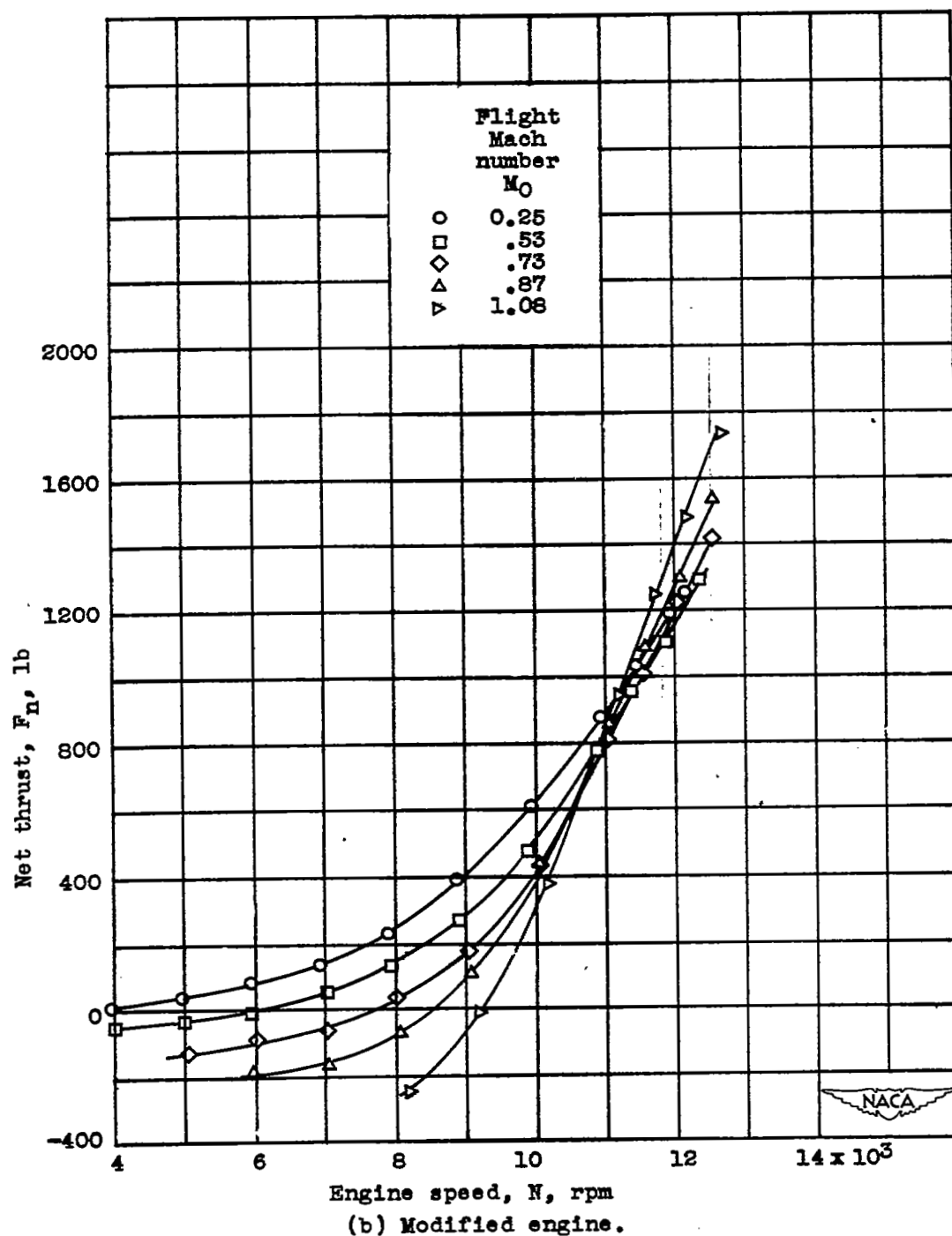
Figure 9. — Concluded. Effect of flight Mach number on variation
of net thrust with engine speed. Altitude, 25,000 feet.
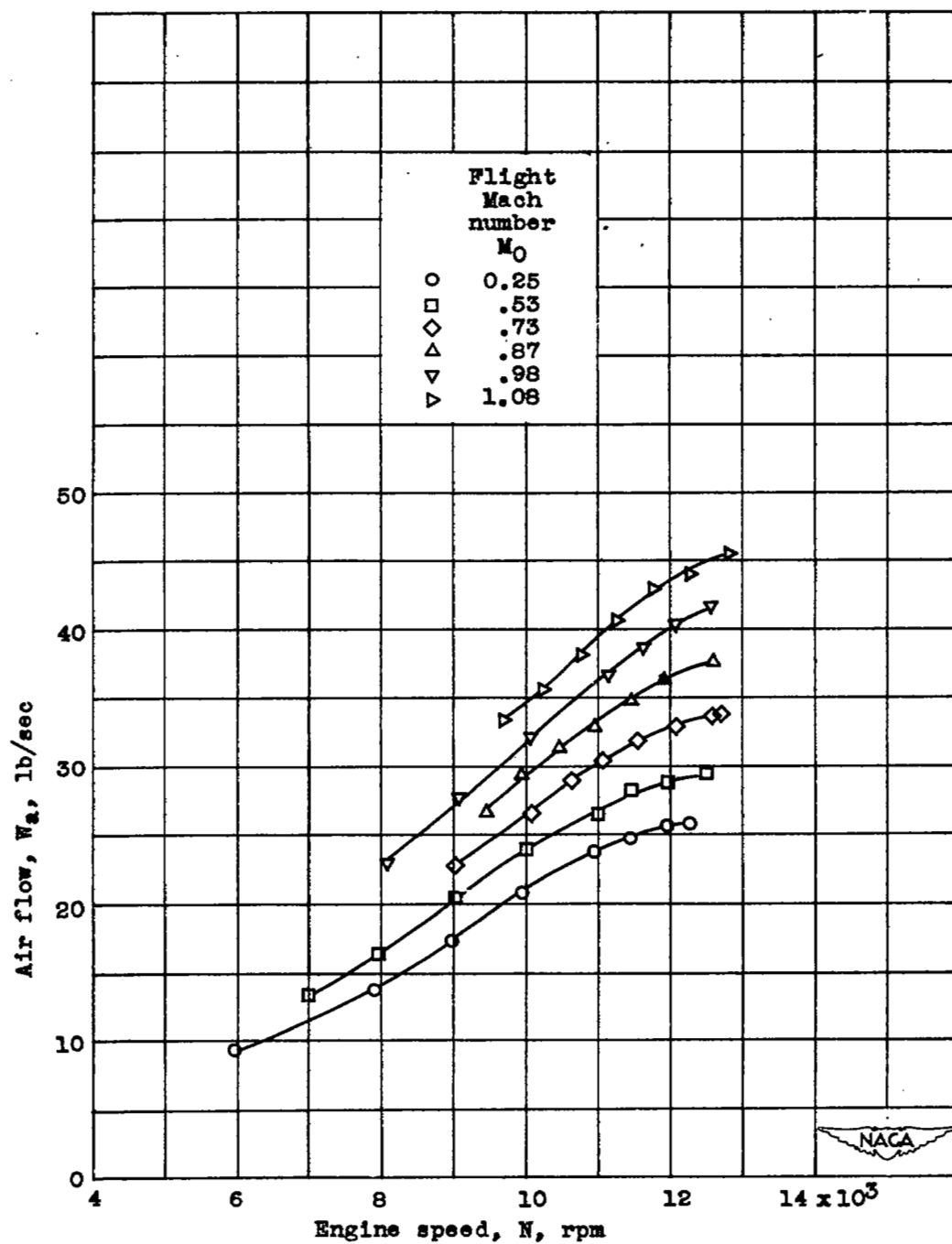
(a) Original engine.

Figure 10. — Effect of flight Mach number on variation of air flow with engine speed. Altitude, 25,000 feet.
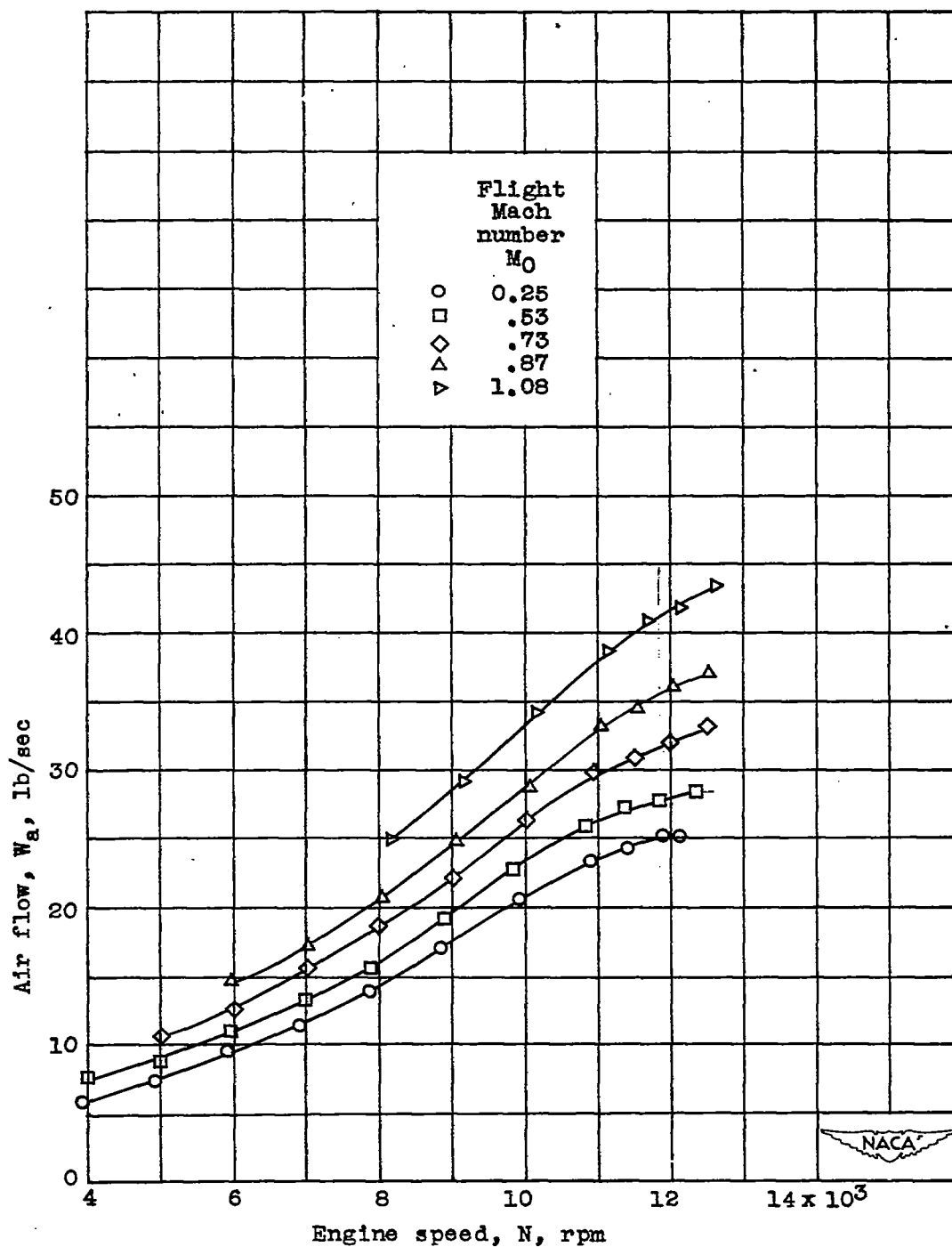
Figure 10. – Concluded. Effect of flight Mach number on variation of air flow with engine speed. Altitude, 25,000 feet.
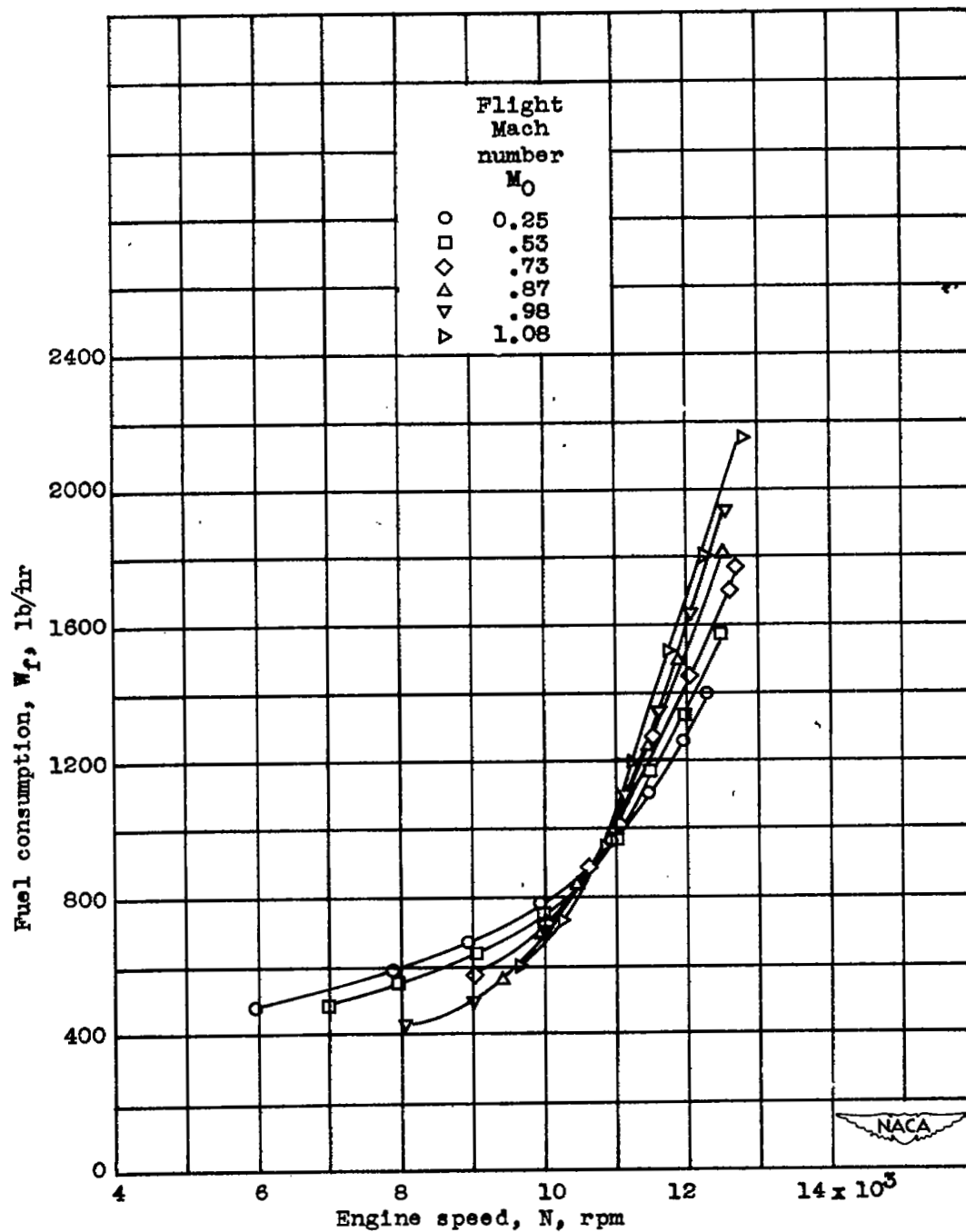
(a) Original engine.

Figure 11. - Effect of flight Mach number on variation of fuel
consumption with engine speed. Altitude, 25,000 feet.

(b) Modified engine.
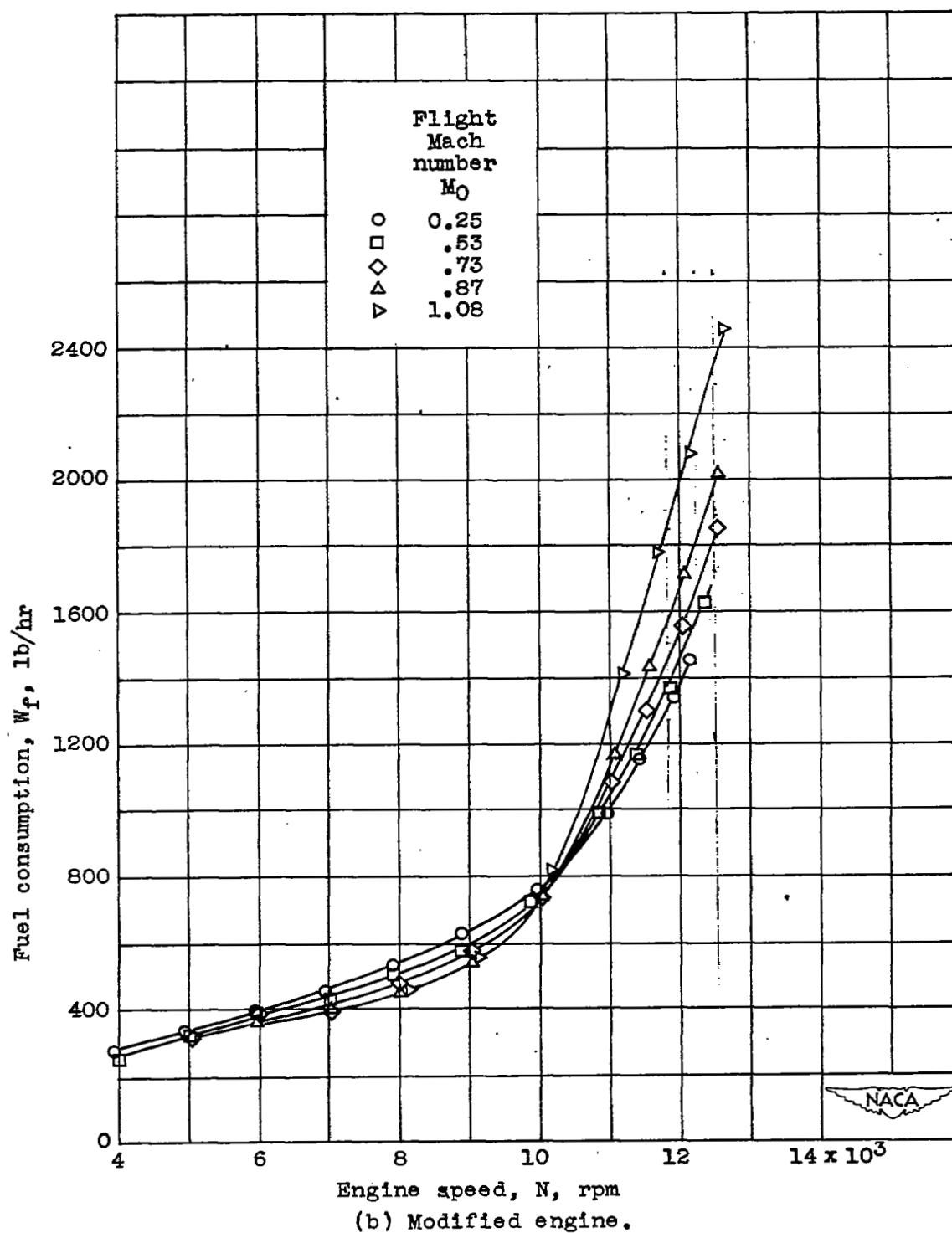
Figure 11. – Concluded. Effect of flight Mach number on variation of fuel consumption with engine speed. Altitude, 25,000 feet.
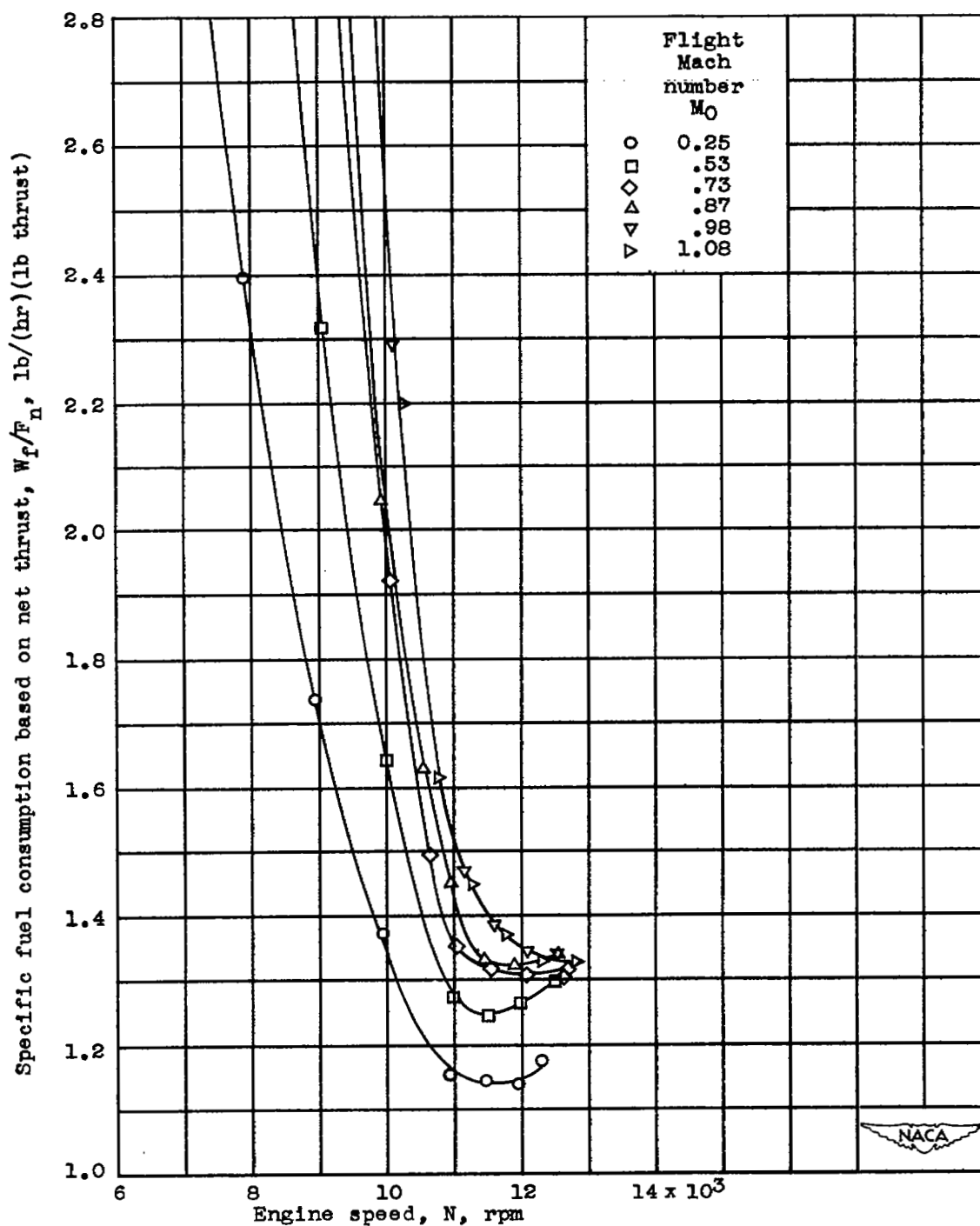
(a) Original engine.

Figure 12. — Effect of flight Mach number on variation of specific
fuel consumption based on net thrust with engine speed. Altitude,
25,000 feet.

(b) Modified engine.
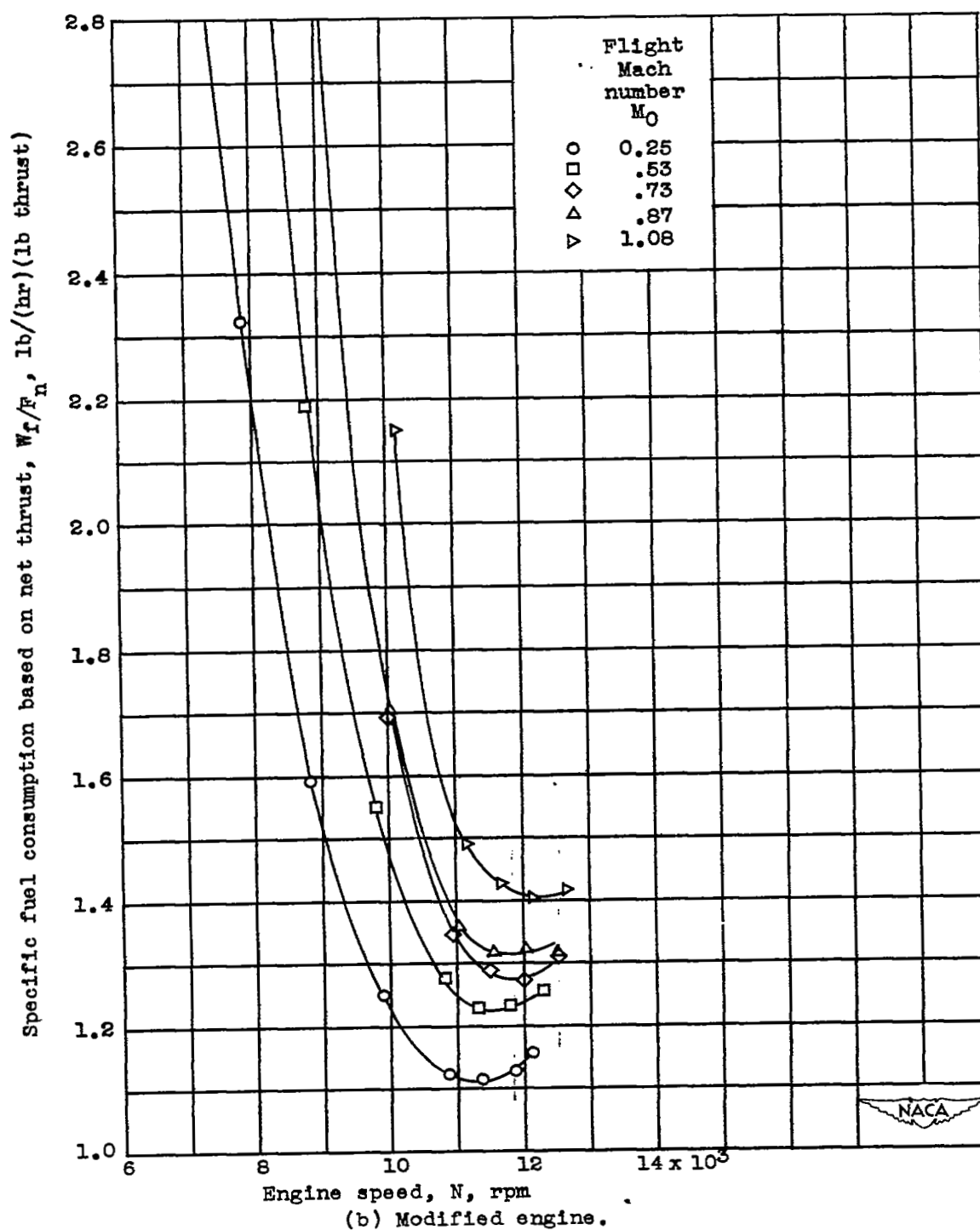
Figure 12. — Concluded. Effect of flight Mach number on variation of specific fuel consumption based on net thrust with engine speed. Altitude, 25,000 feet.

(a) Original engine.
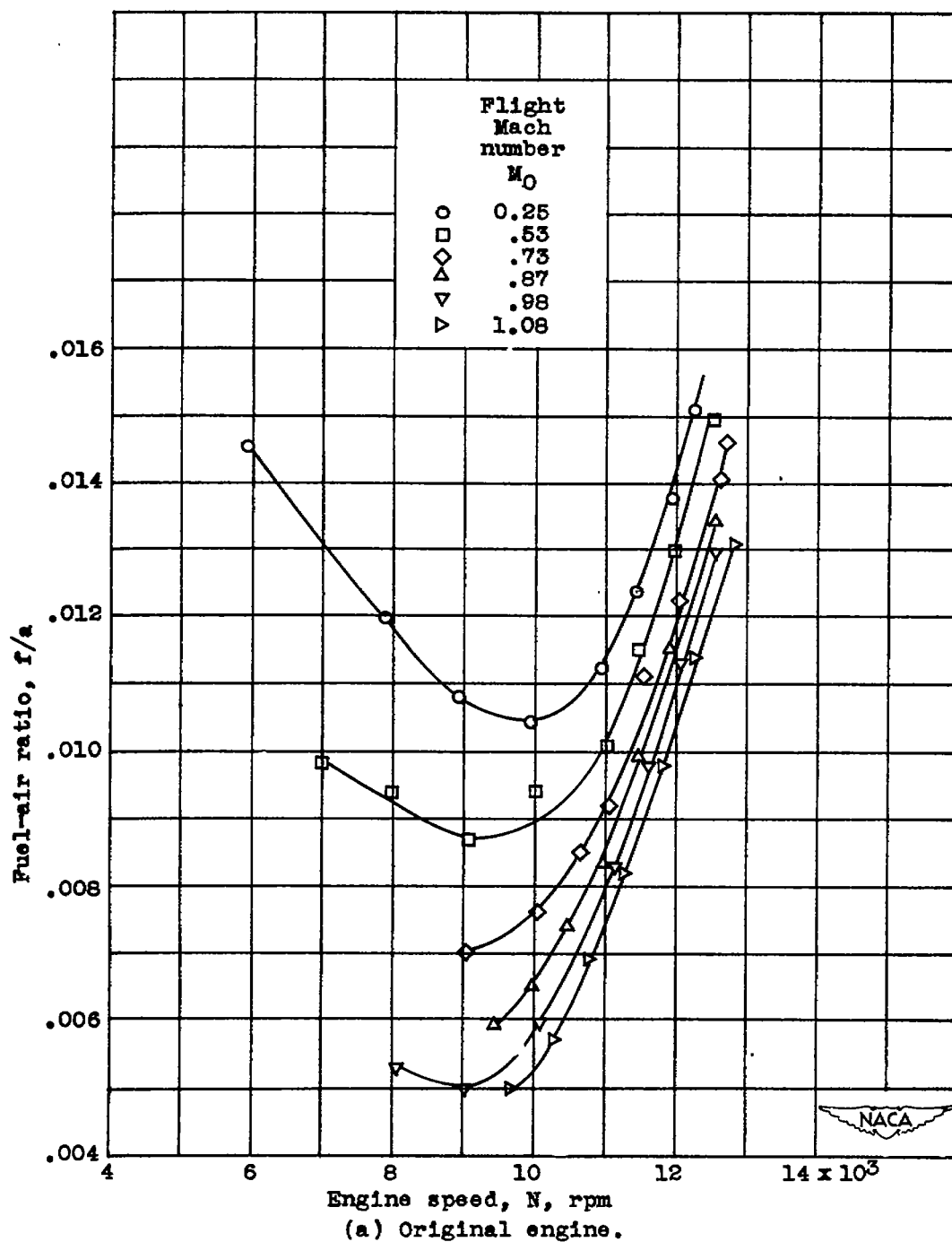
Figure 13. — Effect of flight Mach number on variation of fuel-
air ratio with engine speed. Altitude, 25,000 feet.

(b) Modified engine.
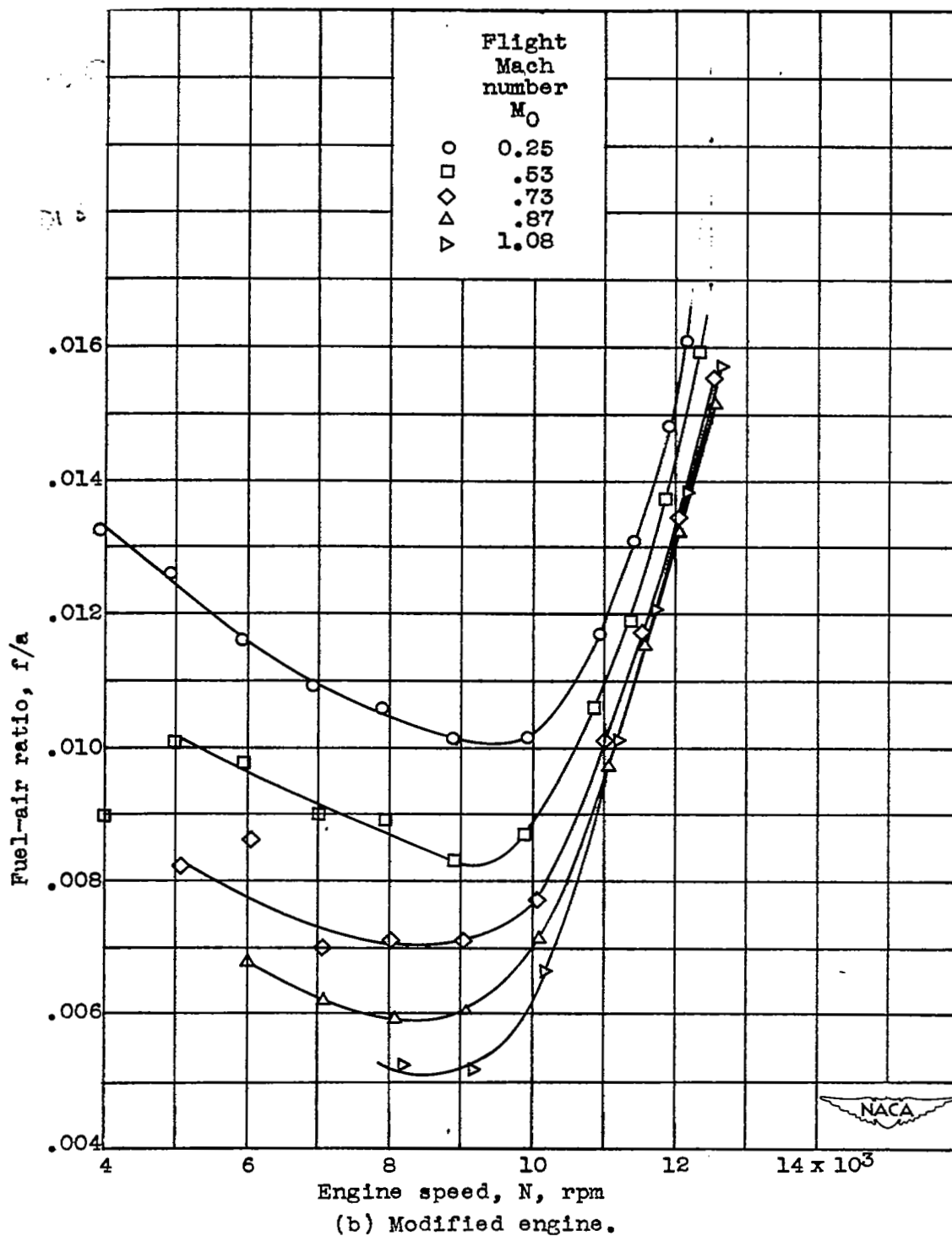
Figure 13. – Concluded. Effect of flight Mach number on variation of fuel-air ratio with engine speed. Altitude, 25,000 feet.

(a) Original engine.
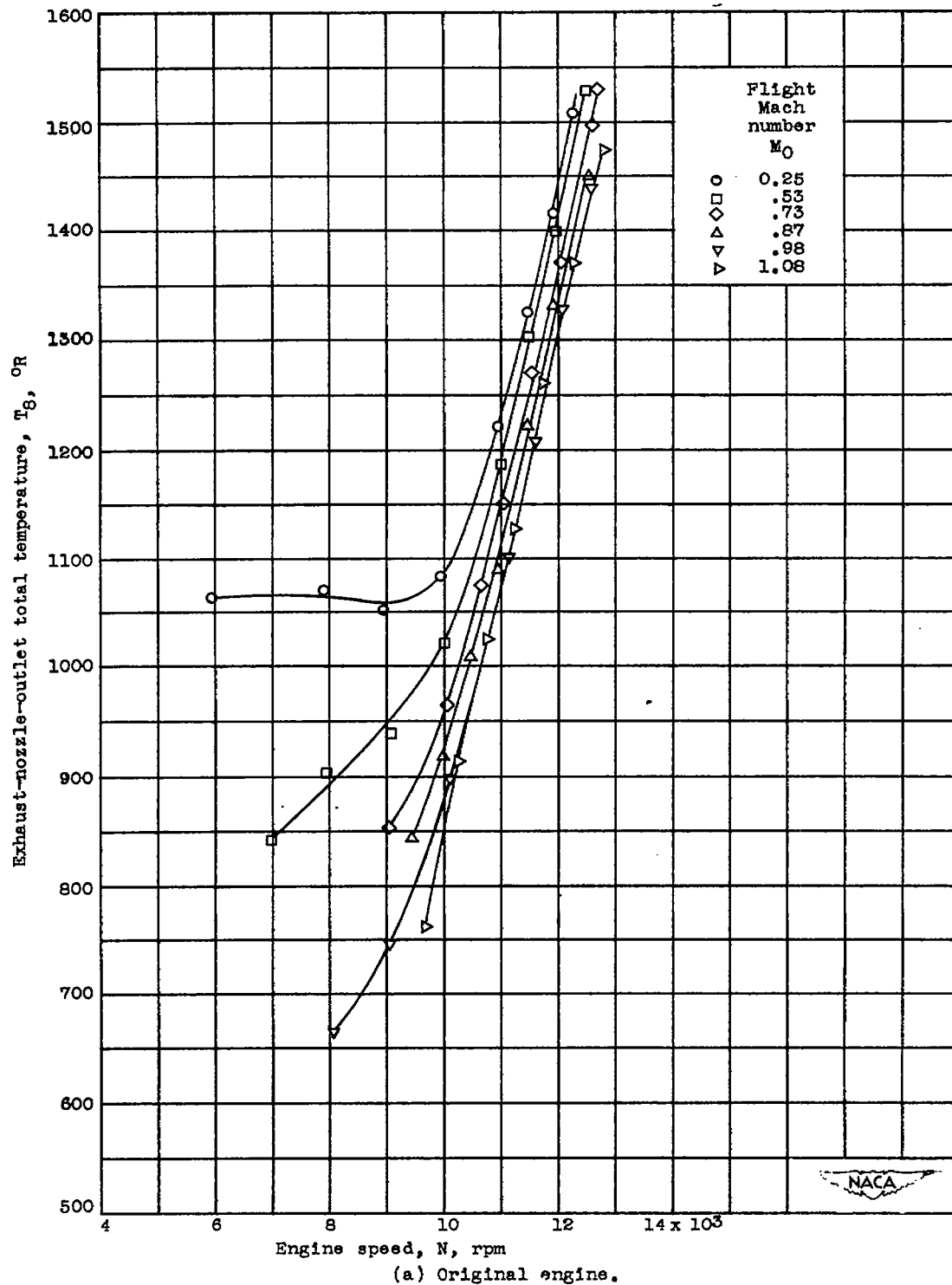
Figure 14. — Effect of flight Mach number on variation of exhaust-nozzle-
outlet total temperature with engine speed. Altitude, 25,000 feet.

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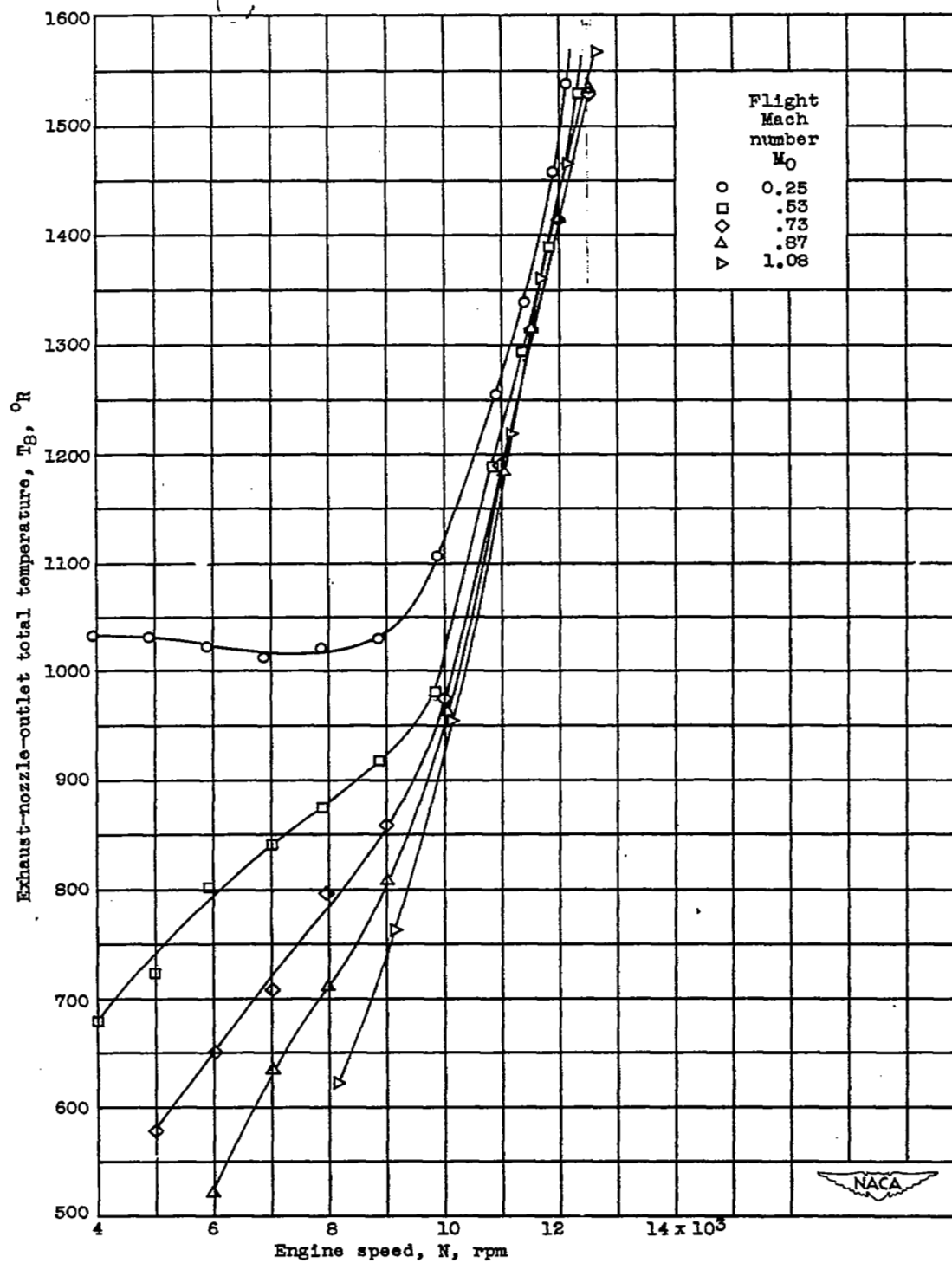
(b) Modified engine.

Figure 14. - Concluded. Effect of flight Mach number on variation of exhaust-nozzle-outlet total temperature with engine speed. Altitude, 25,000 feet.
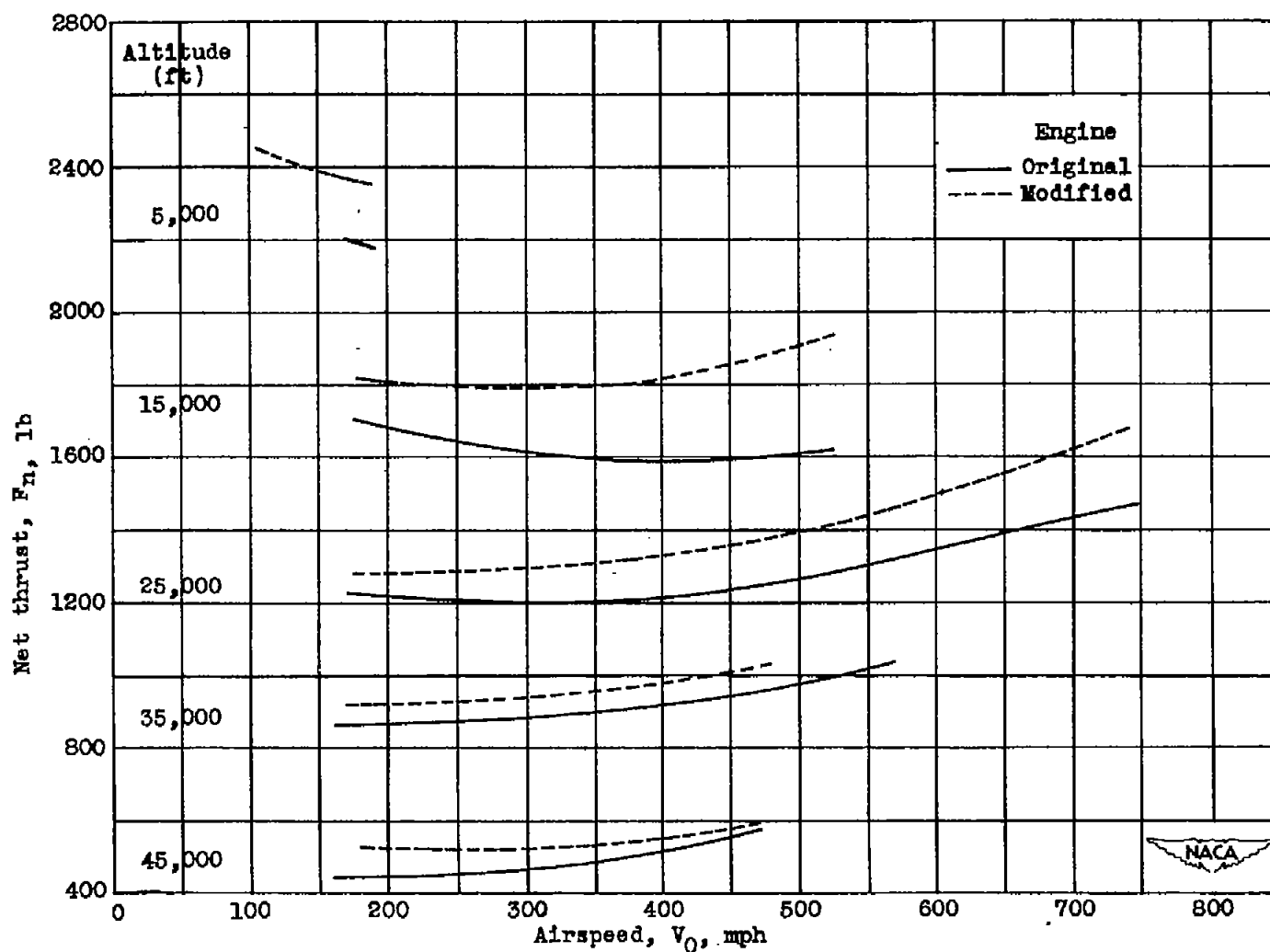
Figure 15. - Variation of net thrust with airspeed at maximum engine speed.
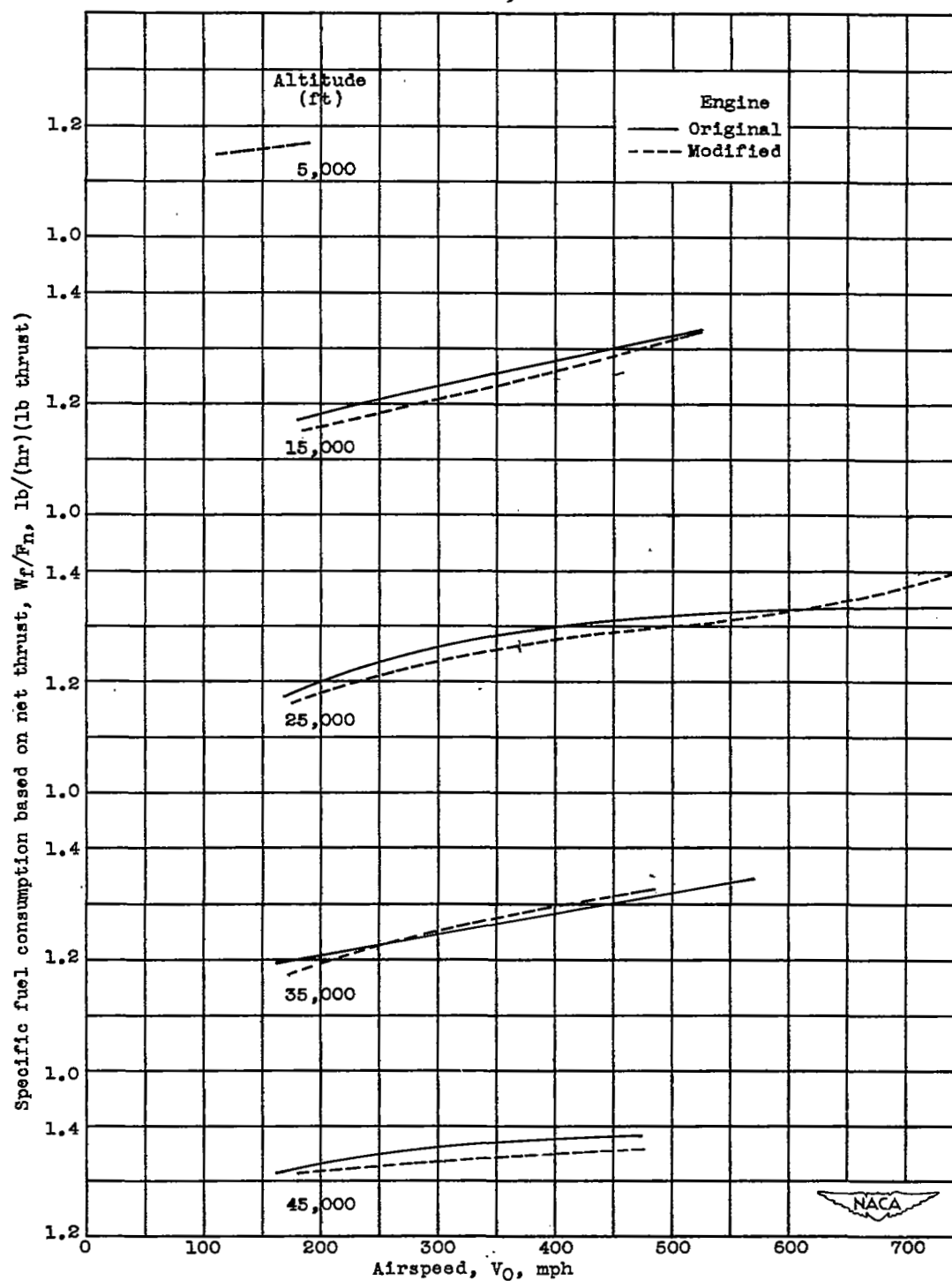
Figure 16. — Variation of specific fuel consumption based on net thrust with airspeed at maximum engine speed.
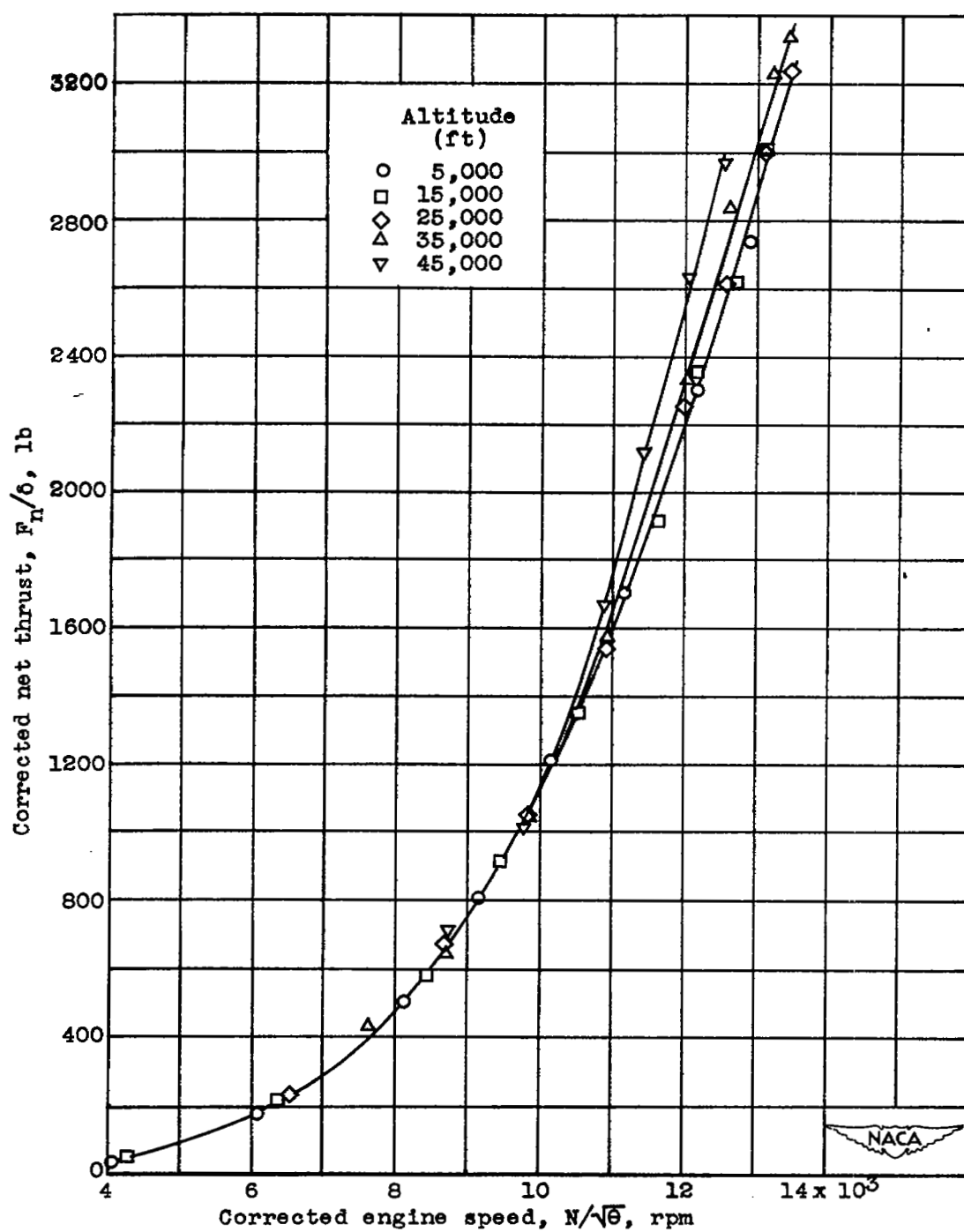
(a) Original engine.

Figure 17. - Effect of altitude on variation of corrected net thrust with corrected engine speed. Flight Mach number, 0.25.

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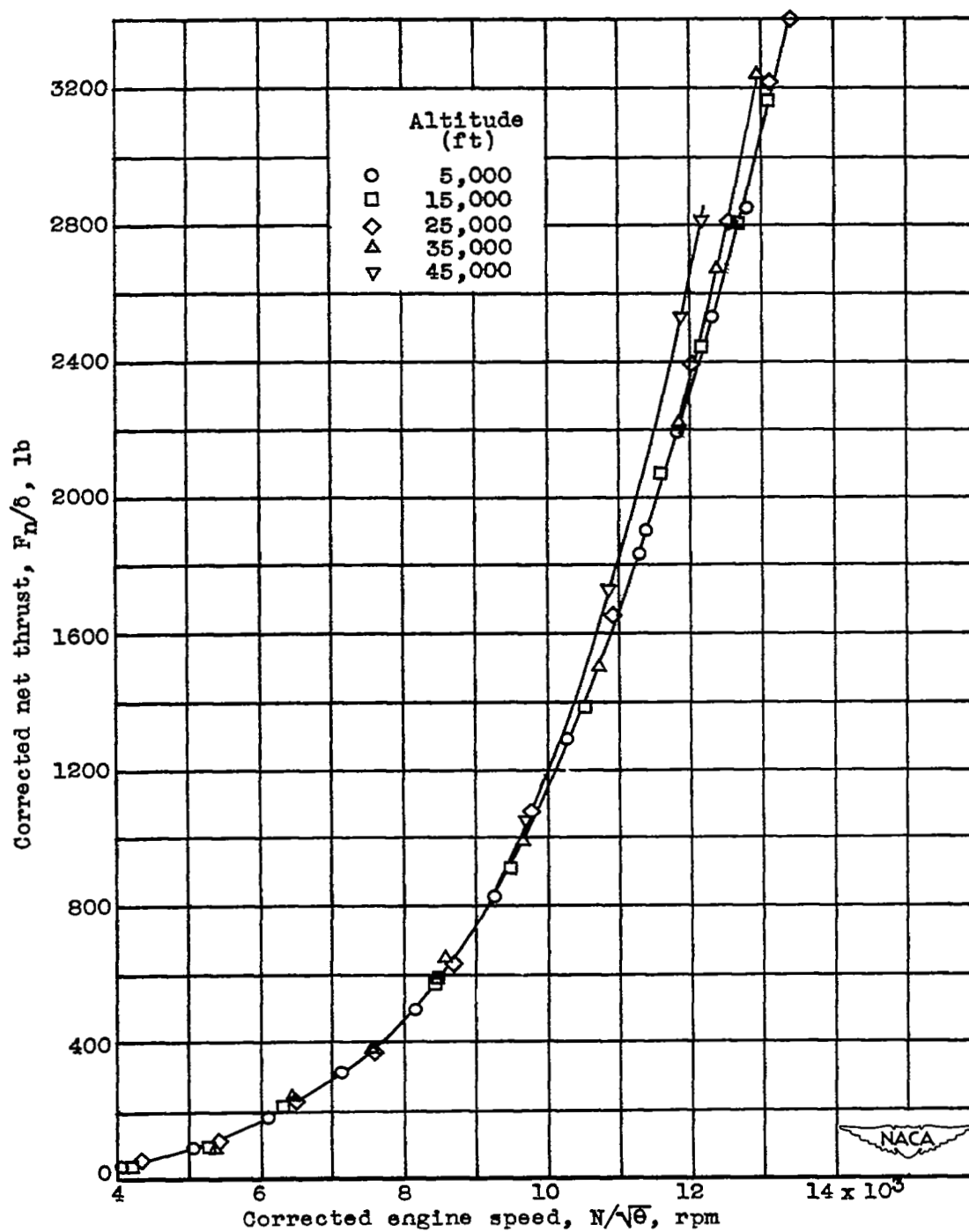
(b) Modified engine.

Figure 17. – Concluded. Effect of altitude on variation of corrected net thrust with corrected engine speed. Flight Mach number, 0.25.
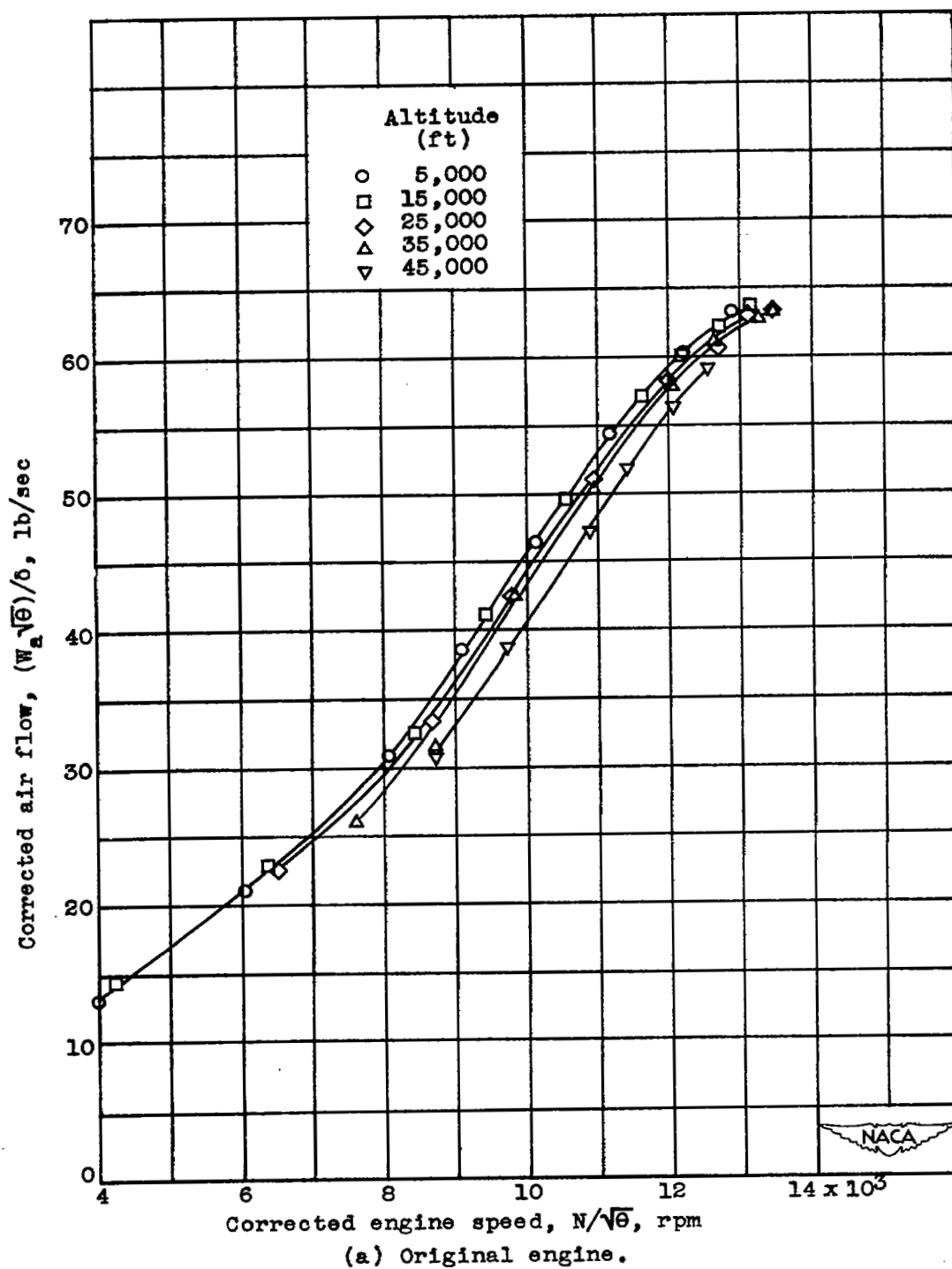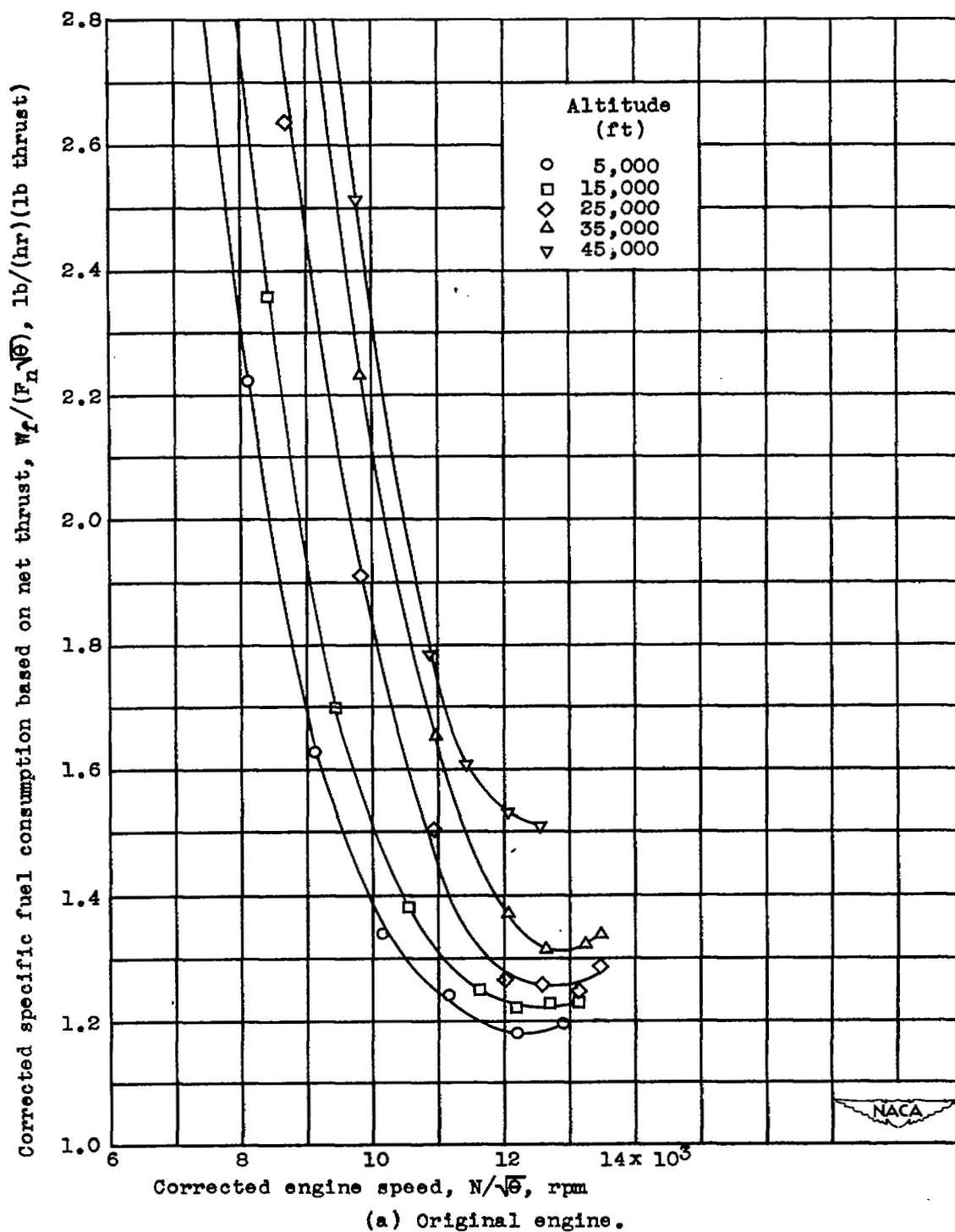
Figure 18. — Effect of altitude on variation of corrected air flow with corrected engine speed. Flight Mach number, 0.25.

(b) Modified engine.
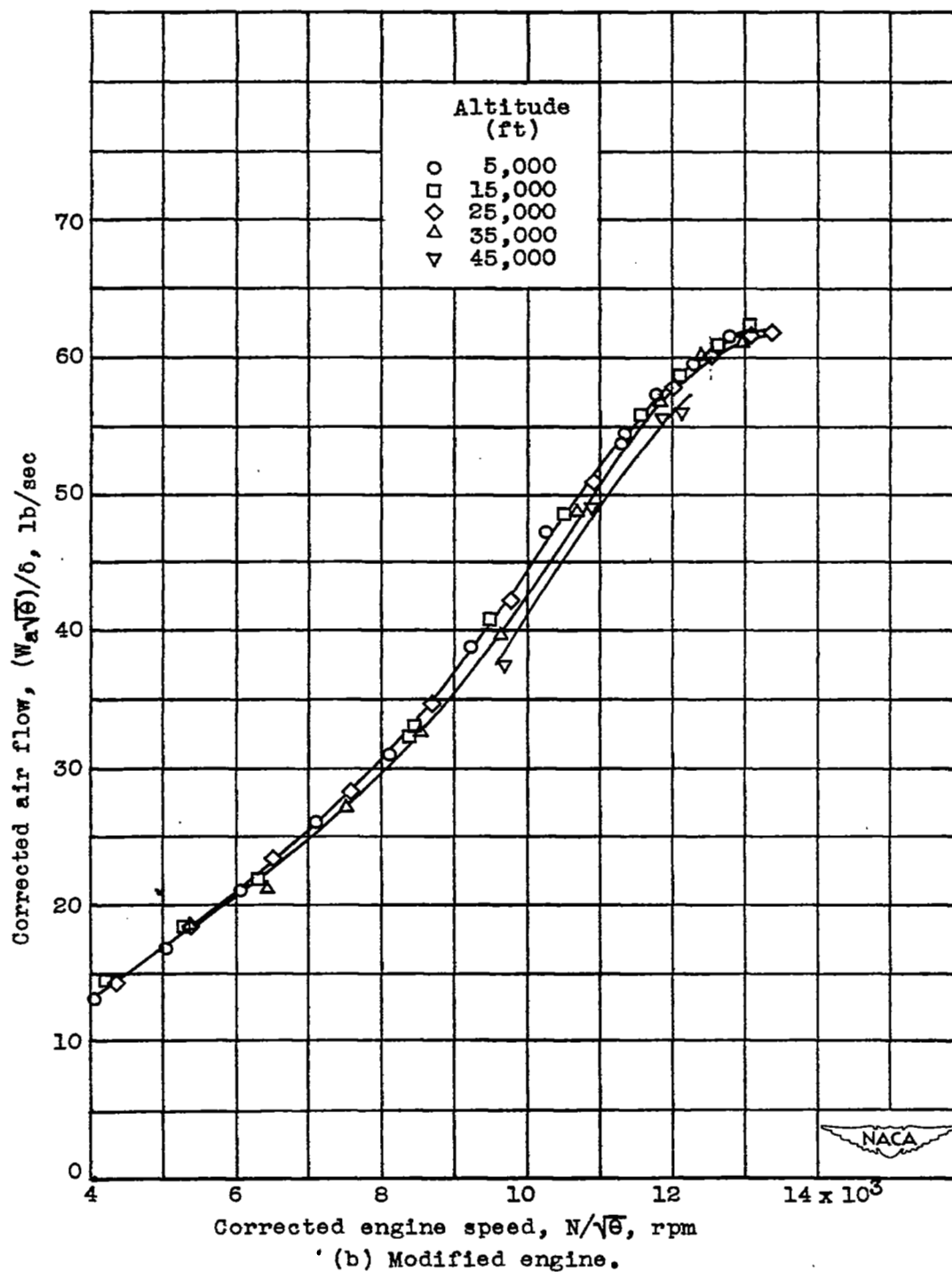
Figure 18. - Concluded. Effect of altitude on variation of corrected air flow with corrected engine speed. Flight Mach number, 0.25.
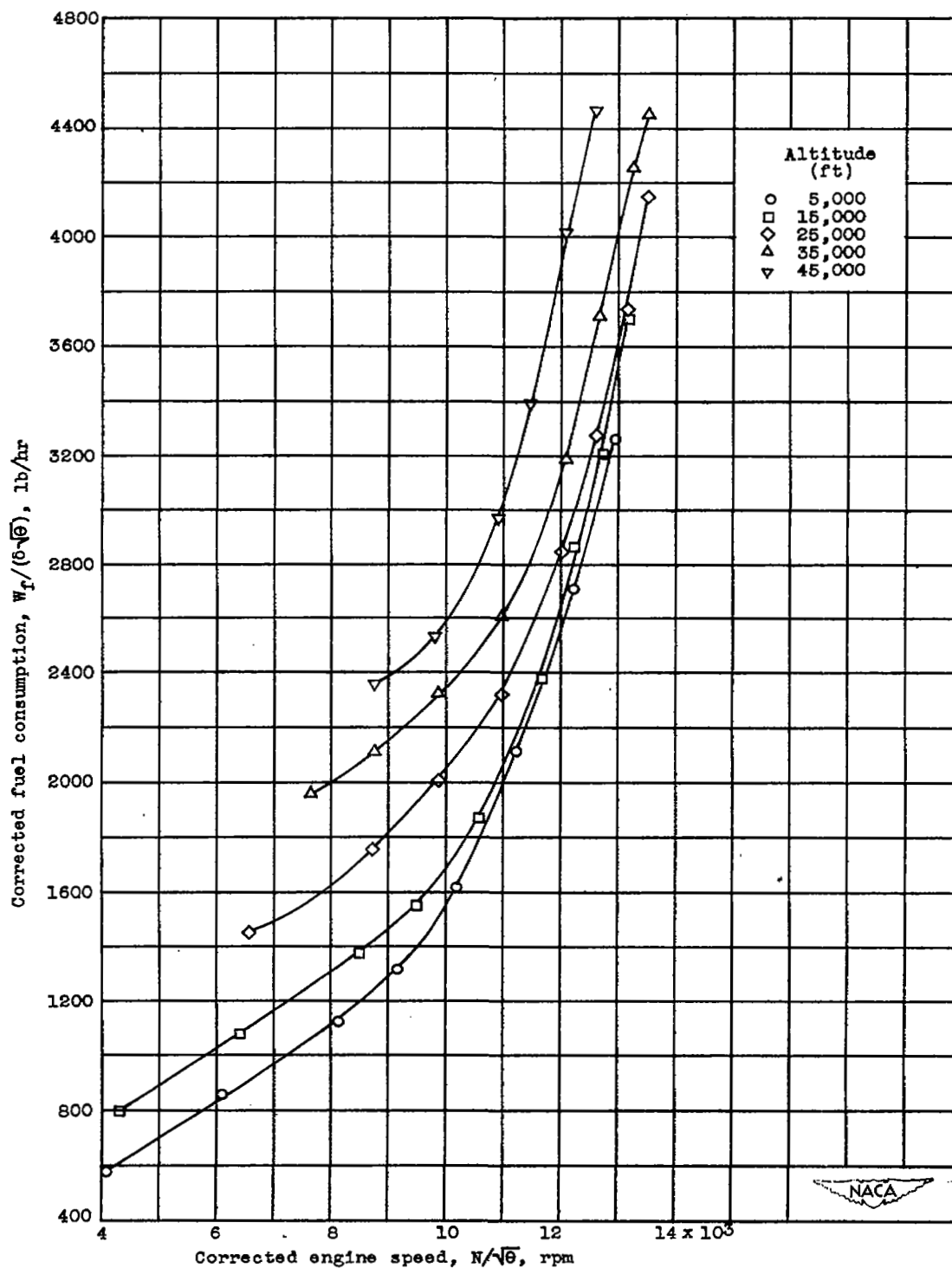
(a) Original engine.

Figure 19. — Effect of altitude on variation of corrected fuel consumption
with corrected engine speed. Flight Mach number, 0.25.
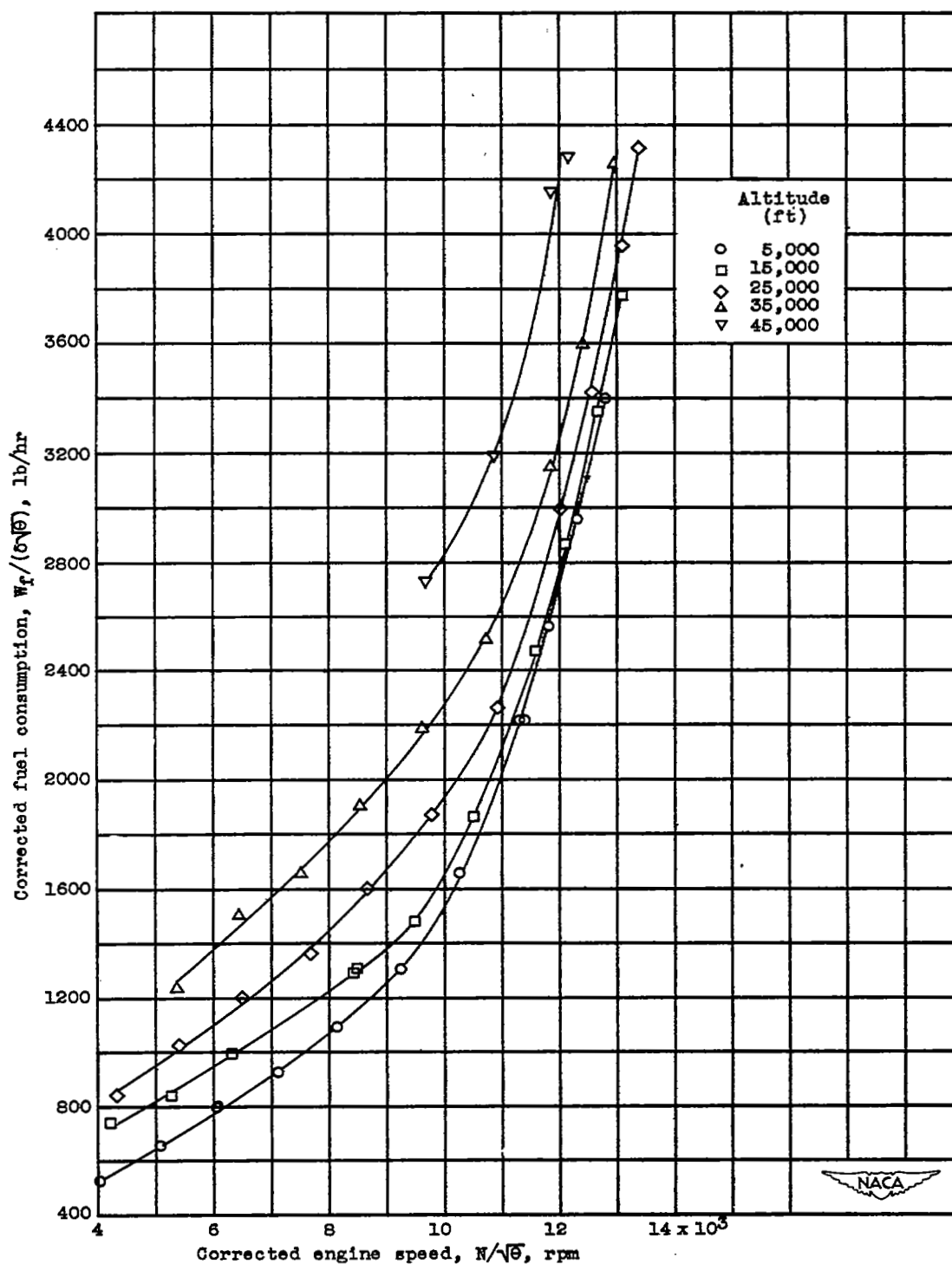
(b) Modified engine.

Figure 19. - Concluded. Effect of altitude on variation of corrected fuel
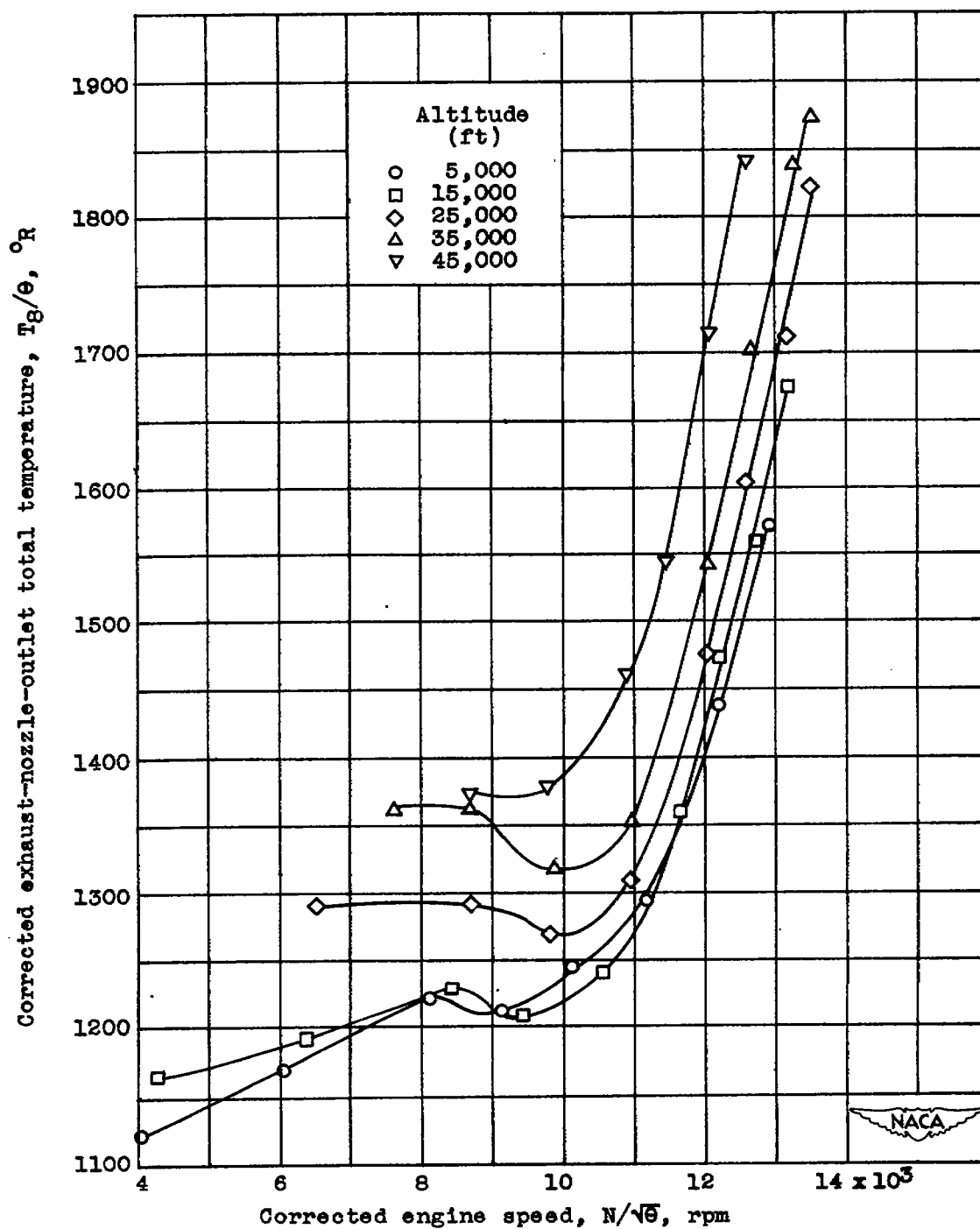consumption with corrected engine speed. Flight Mach number, 0.25.

(a) Original engine.

Figure 20. — Effect of altitude on variation of corrected specific
fuel consumption based on net thrust with corrected engine speed.

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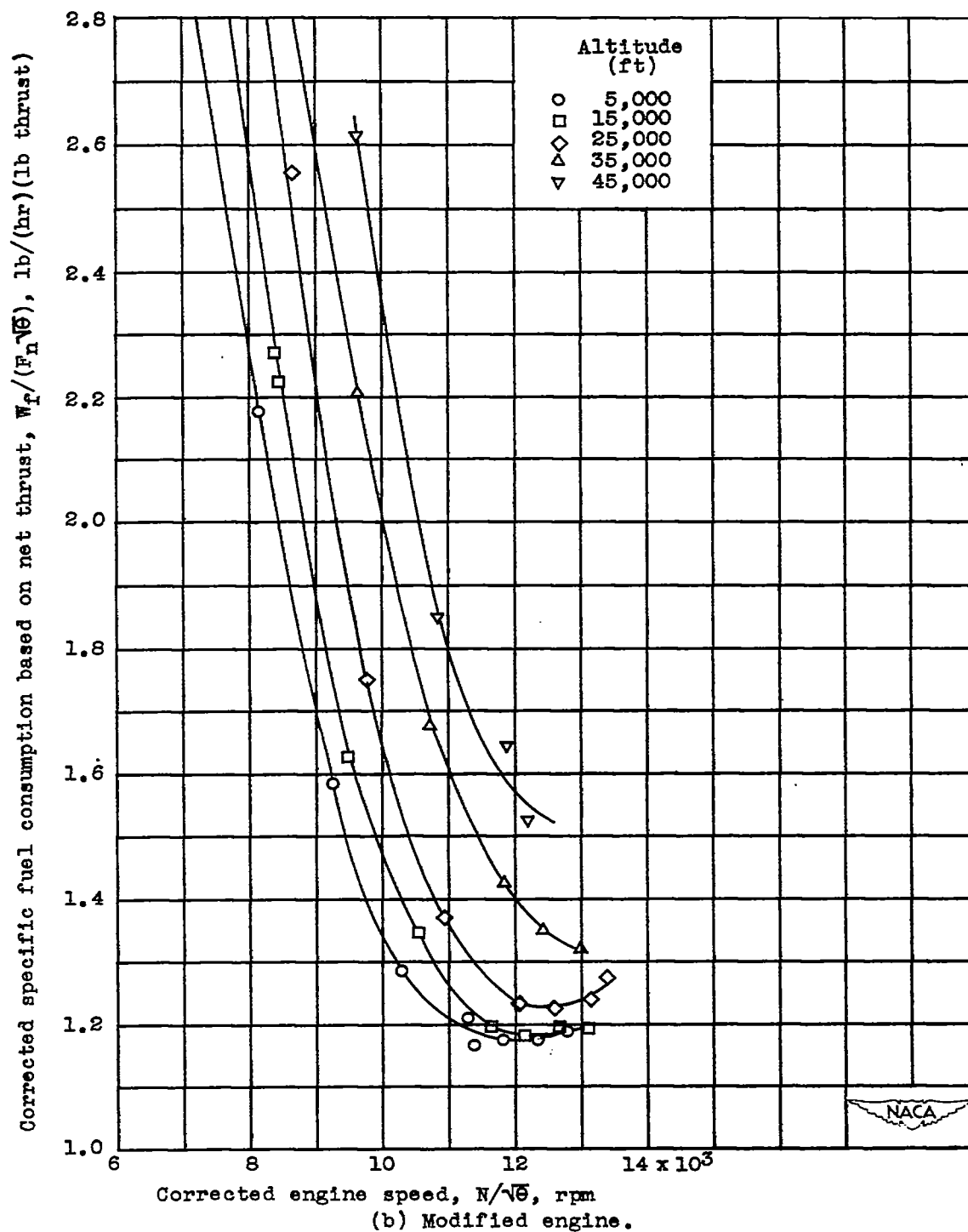
Figure 20. – Concluded. Effect of altitude on variation of
corrected specific fuel consumption based on net thrust with
corrected engine speed.
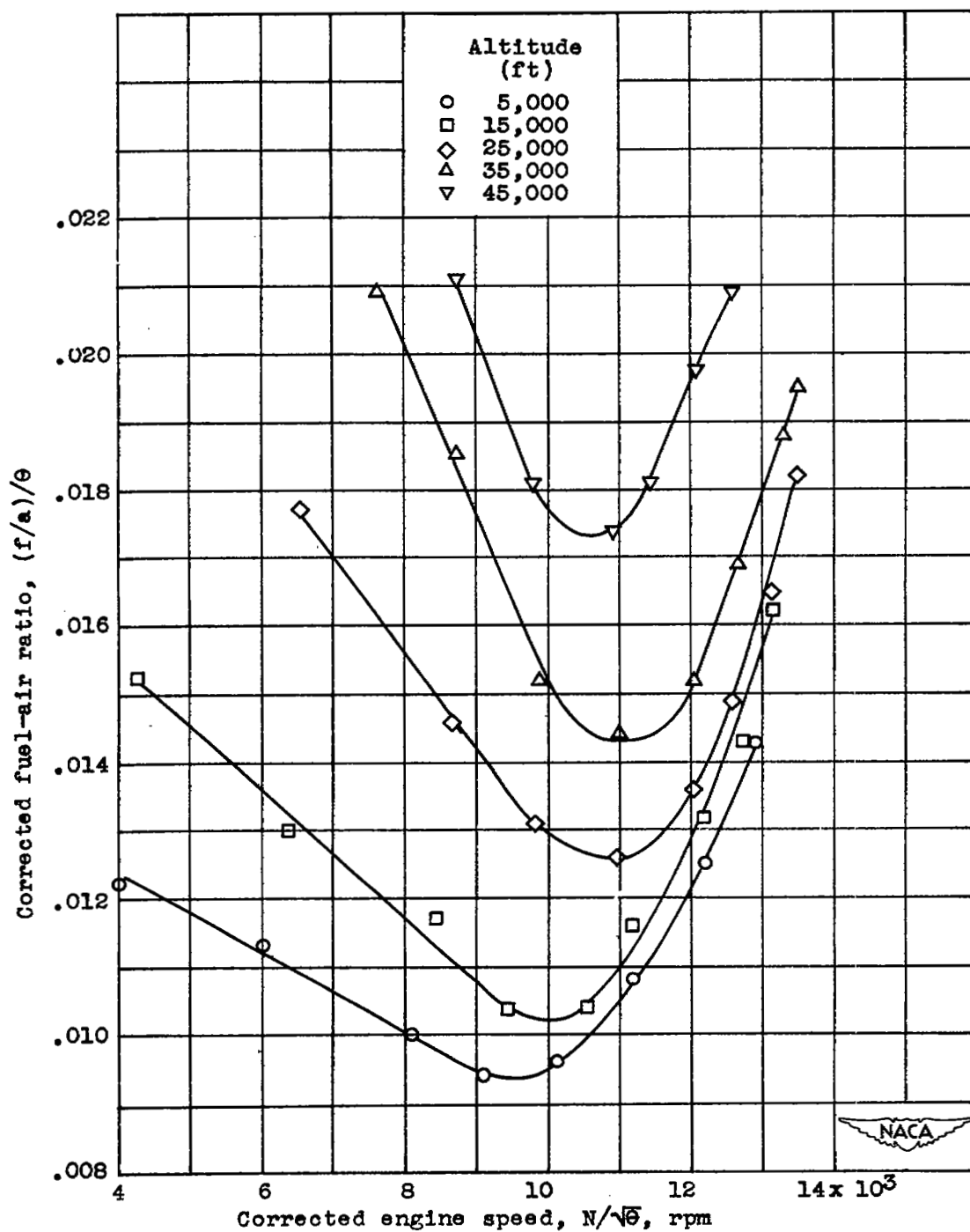
(a) Original engine.

Figure 21. – Effect of altitude on variation of corrected fuel-
air ratio with corrected engine speed. Flight Mach number,
0.25.
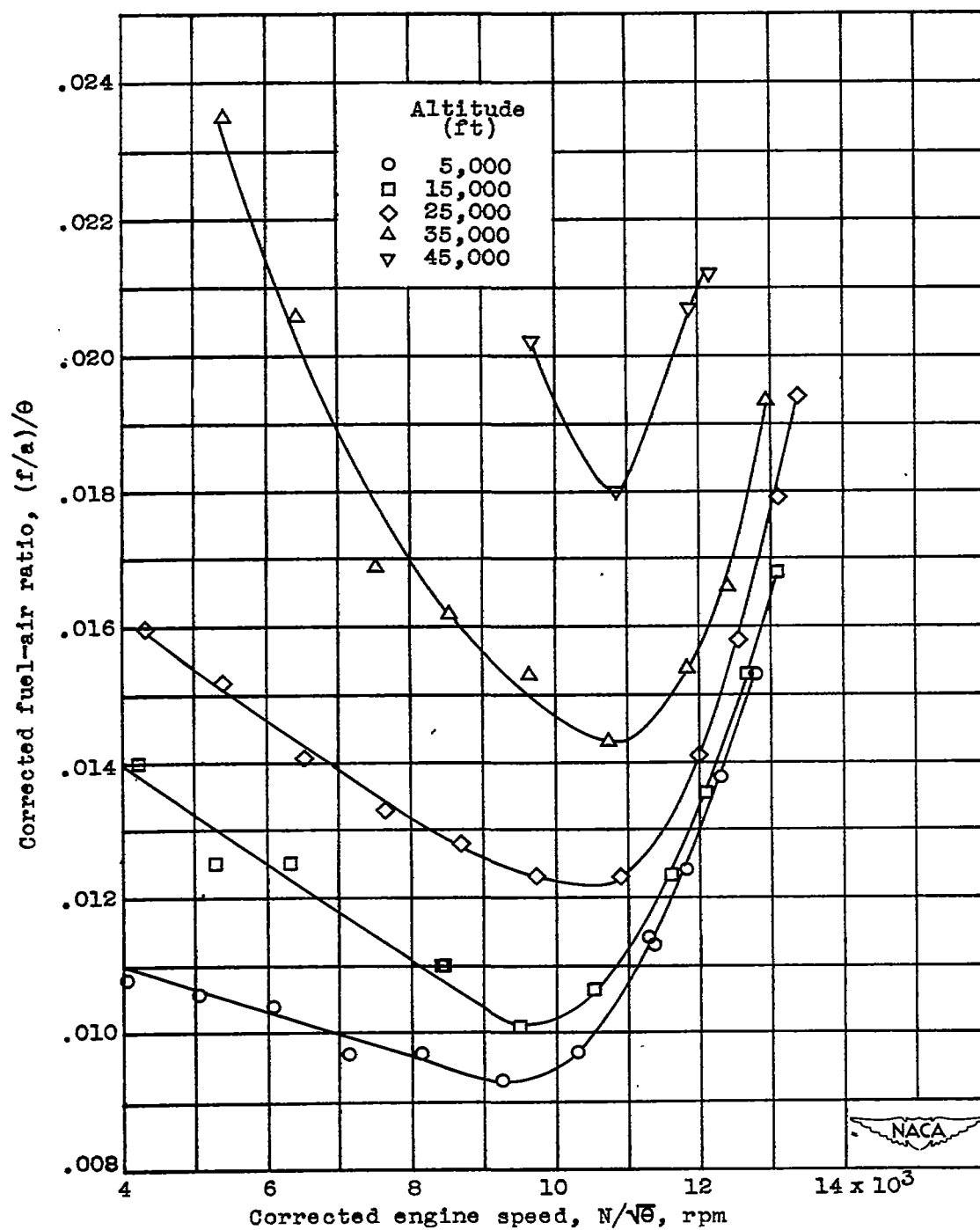
(b) Modified engine.

Figure 21. — Concluded. Effect of altitude on variation of
corrected fuel—air ratio with corrected engine speed. Flight
Mach number, 0.25.

(a) Original engine.

Figure 22. – Effect of altitude on variation of corrected
exhaust-nozzle-outlet total temperature with corrected engine
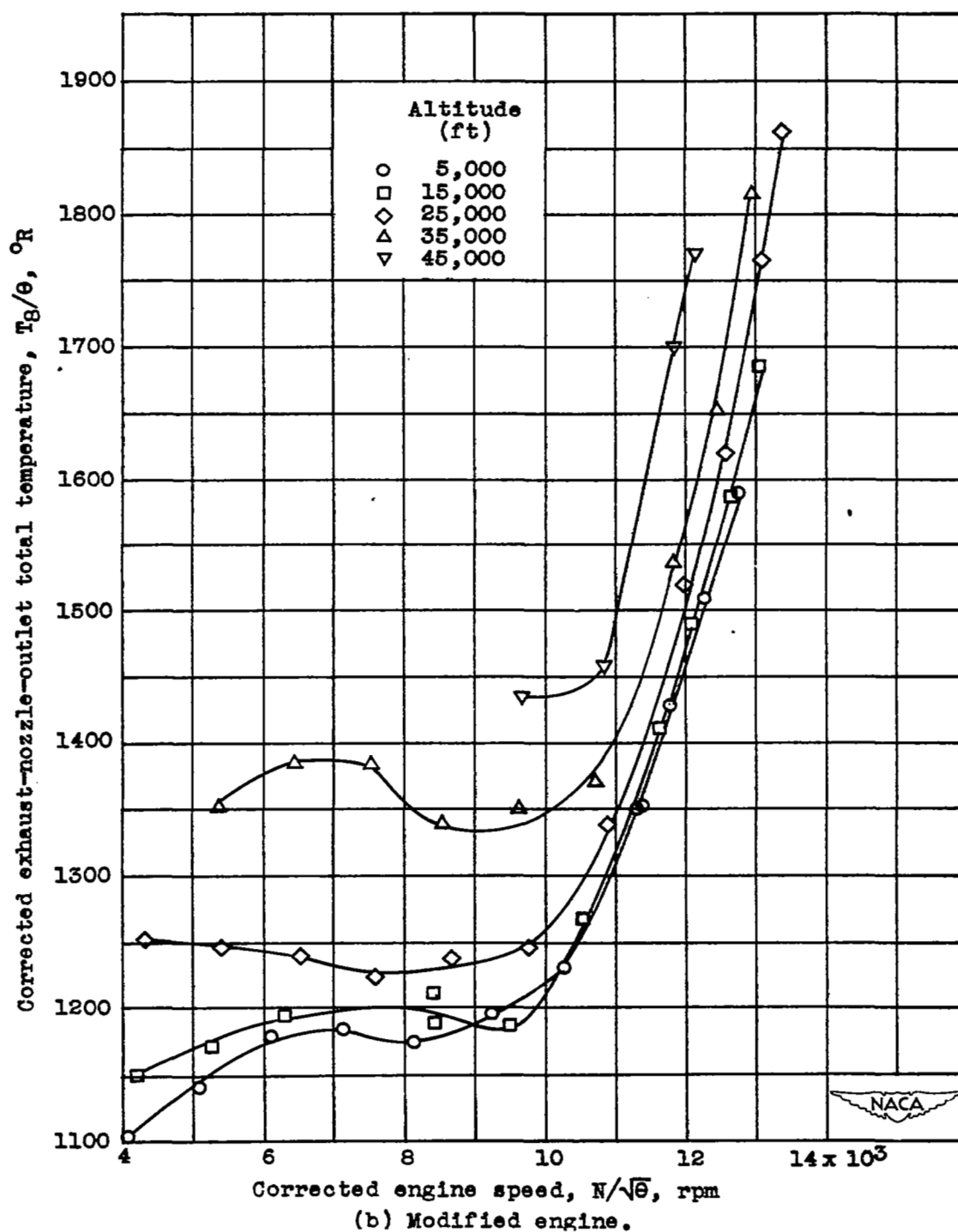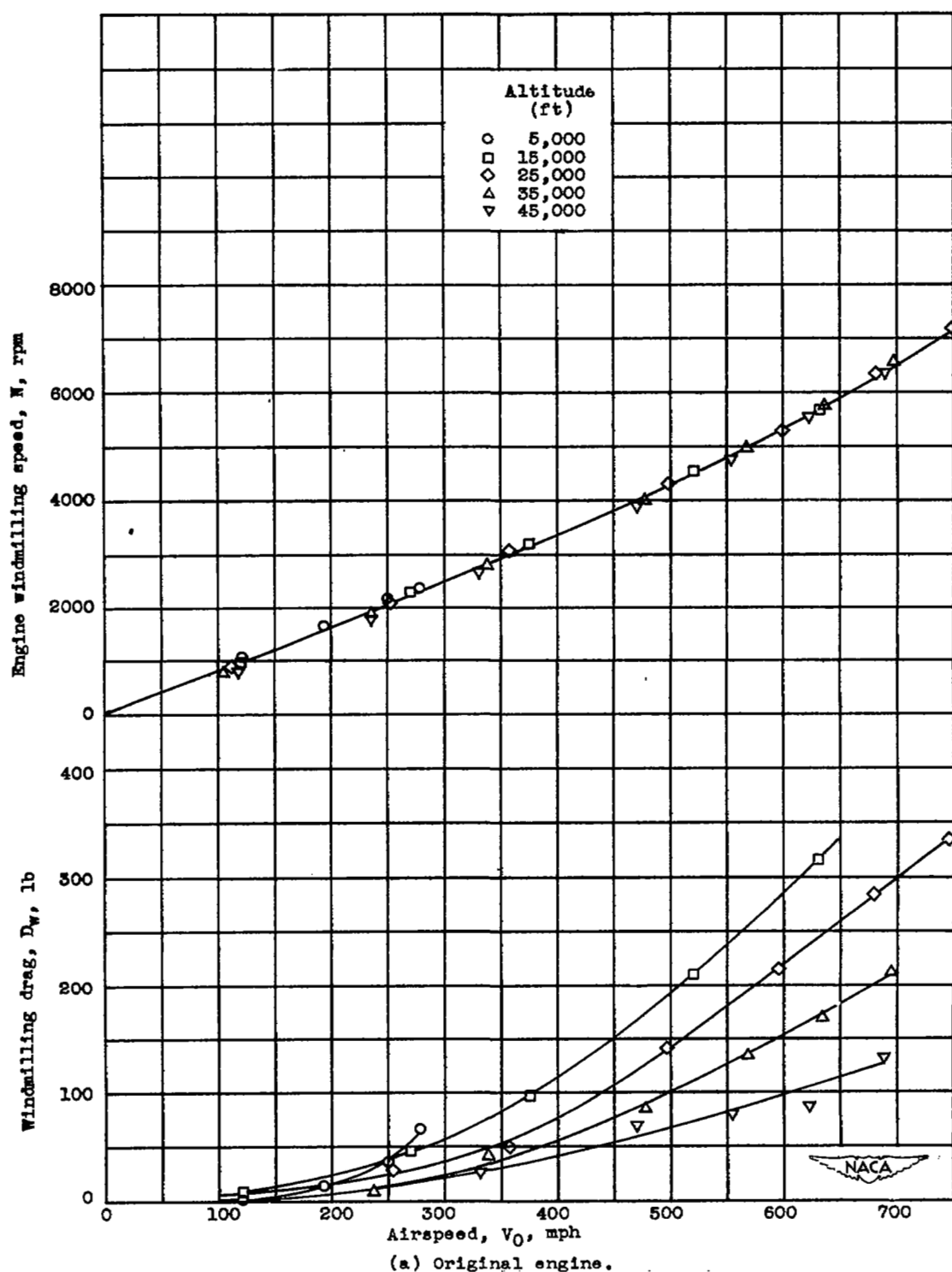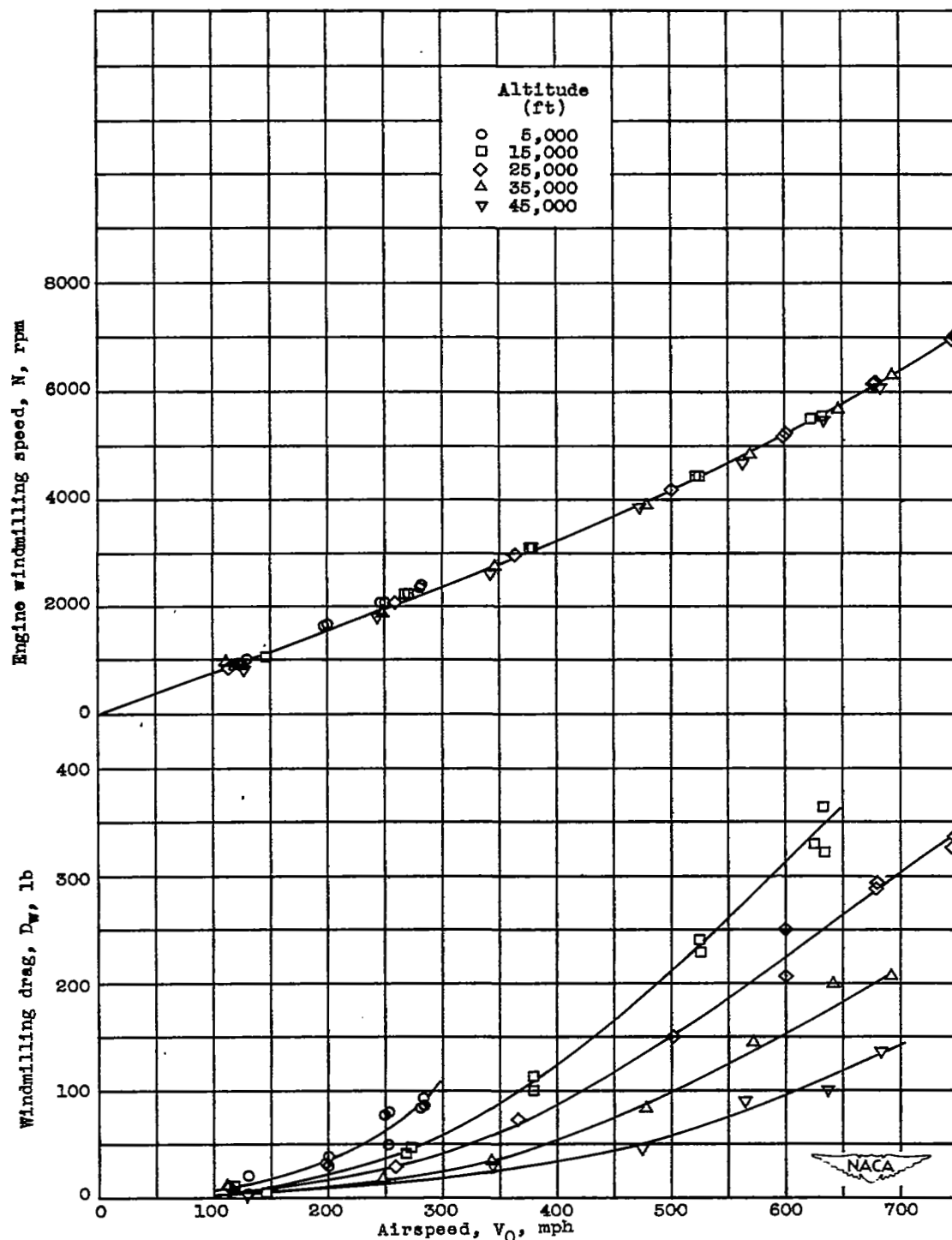speed. Flight Mach number, 0.25.

(b) Modified engine.

Figure 22. — Concluded. Effect of altitude on variation of
corrected exhaust-nozzle-outlet total temperature with
corrected engine speed. Flight Mach number, 0.25.

(a) Original engine.

Figure 23. – Variation of engine windmilling speed and windmilling drag with airspeed.

(b) Modified engine.

Figure 23. — Concluded.   Variation of engine windmilling speed and windmilling
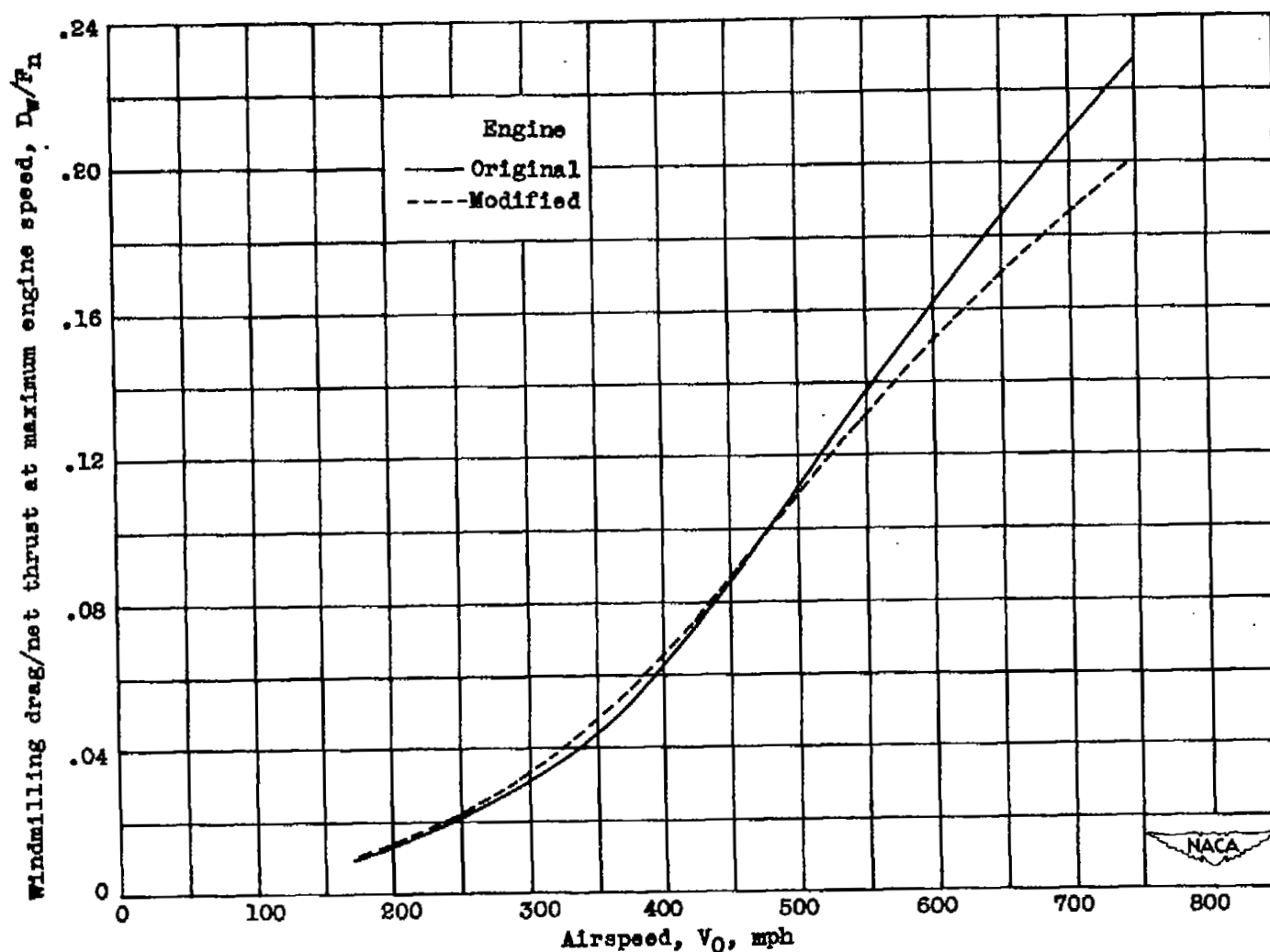drag with airspeed.

Figure 24. - Variation of ratio of windmilling drag to net thrust at maximum engine speed with airspeed. Altitude, 25,000 feet.